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STATUS OF RESEARCH IN AMERICAN GEOGRAPHY

One of a series of ten reports prepared by Committees of the Division of Geology and Geography, National Research Council, under contract with the Office of Naval Research

Contract N7onr-29124

PHYSICAL GEOGRAPHY

Hoyt Lemons,
Chairman

DIVISION OF GEOLOGY AND GEOGRAPHY
NATIONAL RESEARCH COUNCIL
WASHINGTON, D. C.

1952

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REPORT ON PHYSICAL GEOGRAPHY

of the

COMMITTEE ON PHYSICAL GEOGRAPHY AND BIOGEOGRAPHY

Hoyt Lemons, Chairman

Carleton P. Barnes
Kirk Bryan (deceased)
C. J. Burke
George B. Cressey
P. E. James
C. F. Jones
A. W. Küchler
Douglas H. K. Lee
John Leighly
Luna B. Leopold
Jacques M. May
Howard A. Meyerhoff
Louis C. Peltier
Finn Ronne
Richard J. Russell
Laurence C. Stuart
Sir Hubert Wilkins

Division of Geology and Geography

National Research Council

This is one of ten reports prepared to evaluate and describe the current status and future potential of research in various fields of American Geography. The coordinators of the study were Preston E. James and Clarence F. Jones.

National Academy of Sciences - National Research Council

Washington, D. C.

1953

PHYSICAL GEOGRAPHY

This chapter in completed form will
have the following page numbers:

INTRODUCTION

This section is not to be included in the volume, and is therefore missing in this preliminary copy.

(Preston E. James, Chairman, Committee on American Geography)

CLIMATOLOGY

Early Development

Beginnings. In the United States the middle of the twentieth century marks the close of a significant hundred-year period in the study of climate. The time before 1850 might appropriately be called the cradle-age of our climatology. Most of our climatologic works of that period are included in a series of publications issued by the Surgeon-General's office of the United States Army /1/. The concern of responsible medical officers with weather and climate arose from the prevalence among the widely scattered troops of the Army of diseases apparently related to climate. Specifically, men stationed in the Gulf states suffered from malarial and dysenteric ailments more than did those in the northern states. The most important source of climatology in our country, most important because of the wide distribution of stations at which observations were made according to standard regulations, was thus in the deficiencies of medical science in the early nineteenth century. The observations made at military posts formed the only general body of climatologic data accumulated before the Smithsonian Institution established its net of observing stations in the late eighteen-forties.

The results of these observations were made known in a series of publications which with time became ever bulkier /2/. Out of them came the first general work on the climate of the United States, by Samuel Forry (1811-1844) /3/, who had earlier worked up the "Meteorological Register" and the "Statistical Report on the Sickness and Mortality in the Army of the United States." In his "Climate of the United States," the most important of our

climatologic incunabula, Forry stood firmly on the foundation laid by Alexander von Humboldt. He used Humboldt's terminology and Humboldt's definition of climate: "the aggregate of all the external circumstances appertaining to each locality in its relation to organic nature." Forry's book contains as a frontispiece the first temperature map of the United States. It bears winter isotherms for 26° and 41° Fahrenheit, summer isotherms for 65° and 81°, and the annual mean isotherm of 51.75° (annual mean for Fort Vancouver on the Columbia), all drawn schematically and without regard to relief. Forry emphasized, as he had earlier in the publications of the Medical Department, the effects on the distribution of temperature of what we should today call "continentality," and of the Great Lakes.

Lorin Blodget and the Smithsonian Institution. There was no sharp break as the nineteenth century passed its meridian; even the persons involved in the study of climate remained in part the same. Forry died untimely; but the next name that is written large in the history of our climatology at the middle of the century, that of Lorin Blodget (1823-1901), is linked with the work of the Medical Department of the Army. With Joseph Henry's initiation of an organized net of observing stations in 1849, under the auspices of the Smithsonian Institution, the investigation of climate moved on to a larger stage. From the time of his assumption of the secretaryship of the newly founded Smithsonian Institution, Henry (1799-1878) directed its funds into work in meteorology. Aside from current observations, which, in accordance with Henry's interests, were primarily undertaken for what would today be called synoptic purposes, the working up of earlier observations was kept in mind. The first larger result of this more strictly climatologic interest, among the publications of the Institution, was James H. Coffin's memoir on the

winds of the northern hemisphere, published in 1854.

As the material from the observing stations accumulated, it became necessary to employ someone to take charge of working them up. Henry employed Blodget for this task, and Blodget entered on his duties at the end of 1851. A year and a half later Blodget began to report publicly on his work. At the meeting of the American Association for the Advancement of Science held in June, 1853, he read four papers, the material of which was drawn from the observations he was working on /4/. And on the same occasion the obverse of Blodget's activity, the displeasure of his superior, Henry, was exhibited in public. Henry reminded his and Blodget's hearers that the material of which Blodget was speaking was collected by certain public agencies, and that these agencies should be credited with it. Friction between Blodget and Henry ended with Blodget's dismissal at the end of 1854, when Henry employed Coffin in his place.

But now two long papers by Blodget appeared, which were later incorporated, in amplified and revised form, into his justly famous "Climatology of the United States" /5/. The first is a work on the agricultural climatology of the United States, published in 1854 /6/. From this came the chapters of the Climatology on the general character of the climate of the various sections of the country, the comparison of these climates with those of Europe, and the capacity of the American climate for agricultural staples. The two other essential chapters in the Climatology, those on the distribution of temperature and precipitation, with their accompanying charts, are revised from a contribution to the Army Meteorological Register for the years 1843-1854 /7/.

Joseph Henry's disapproval of Blodget's work followed him as these

works appeared. In the first of a series of papers on the general subject of meteorology in its connection with agriculture, published in the Agricultural Report of the Commissioner of Patents, 1855 to 1858 /8/, Henry praised the tabular part of the Army Meteorological Register published in 1855, but, without mentioning Blodget's name, decried the temperature maps as "premature publications, constructed from insufficient data, and on a principle of projection by which it is not possible to represent correctly the relative temperatures in mountainous regions."

One can share Henry's adverse opinion of the drawing of isotherms on Blodget's temperature maps. Blodget evidently had no notion of the character of isarithms as indices of the distribution of a continuous variable over a surface; he permitted his to terminate on the map, to bifurcate and anastomose. But what Henry was objecting to in the passage cited was Blodget's treatment of data from the mountainous West, where the scattered stations were all situated in valleys. Blodget used the same procedure as Forry had fifteen years earlier: he drew his isotherms with reference to the valley stations, and explained that the distribution of temperature shown referred to the valleys, and made no pretense of representing the temperatures of elevated tracts. With his second paper in the Reports on Agriculture Henry included a temperature map of the United States of his own construction, and in his text called particular attention to his "reduction" of temperatures to sea level, at a rate of 3^{o}F per thousand feet elevation.

From the preface to Blodget's Climatology of the United States it is clear that what would today be called synoptic and climatologic investigation were split within the Smithsonian Institution while he was employed there. According to his account, he was first assigned to reducing the recently

received observations synoptically, in the manner exemplified by the contemporary work of Elias Loomis. But he found this work unsatisfying, and the climatologic reduction of the observational material much more rewarding. And in his papers in the Reports of the Commissioner of Patents, Henry too made a distinction between the knowledge that can be derived from the statistical handling of observations of the weather, and the possibility of predicting the movement of storms, thus implying that both branches were being pursued at the Smithsonian Institution.

Blodget's Climatology of the United States remains, in spite of its faults, the great monument of American climatology in the Nineteenth century. Its author brought together the material he had published elsewhere, revised his maps, and skilfully fashioned the whole into a rounded scientific and literary fabric. He gave his readers, in truth, God's plenty: tables of observations, maps, quotations from travelers, forceful verbal characterizations. Above all he exemplified the sanguine spirit of the mid-century citizen of the Republic, surveying the imperial expanse of its area, contemplating its immensities, and prophesying its magnificent future. The master to whom he looked for inspiration and example was, as for Forry before him, Humboldt. This he confessed in his preface, where he rather ostentatiously flaunted an appreciative letter from the master, in which he undoubtedly found abundant compensation for the slights he had suffered at Joseph Henry's hands. Humboldt's clear-eyed and comprehensive view of nature was highly congenial to the spirit of the Old Republic, which in 1857, like the aged Humboldt himself, was hastening toward dissolution. It was from Humboldt that Blodget caught the urge to compare the climates and potentialities of the new world with those of the old. In Humboldt's writings,

too, he could find precedents for his tabular and graphic presentations of data. Tables and maps might be improved in the future, and the data subjected to a closer scrutiny; but no later decade could provide the intellectual atmosphere in which such a work as Blodget's could be written. It is no accident that the Climatology is contemporaneous with Walt Whitman's "Song of the Broad-Axe;" both are flowers of the waning years of our intellectual golden day.

Blodget's successor, James H. Coffin (1806-1873), compiled the data for the joint publication of the Smithsonian Institution and the Patent office, issued in two volumes in 1861 and 1864 /9/. He is better remembered for his two memoirs on the winds: the first on the winds of the northern hemisphere, mentioned earlier, and the second on the winds of the whole globe /10/, unfinished at his death and completed by other hands. As early as 1858 Henry had employed Charles A. Schott (1826-1901), since 1855 chief of the computing division of the Coast Survey, to work up special collections of observations. It fell to Schott, a master of computingtechniques and familiar with the pitfalls of observational data, to work up the accumulated material on precipitation and temperature /11/. Schott's maps represent an enormous improvement over Blodget's, not only because he had more material than Blodget had had, but also because he was more attentive to the gradation of the quantities over the surface of the earth, and more conscious of character of isarithms than Blodget ever learned to be.

As examples of the combination of observations, Schott's memoirs have never been surpassed in thehistory of American climatology. In reducing the data on precipitation, he not only drew maps, but also investigated the annual march and computed amounts per day with precipitation, the probable error of means, and secular fluctuations. For his memoir on temperature he compiled

data on the daily march of temperature, comparing the daily march among groups of stations by Fourier analysis to three harmonic terms. He subjected the annual march at 46 stations to the same kind of analysis, and examined the records for possible recurrent irregularities in daily temperatures and for securlar change. In view of Joseph Henry's pronounced preference for the reduction of temperatures to sea level on maps, it is of interest to note that Schott's isotherms represent unreduced surface temperature; and that in his text he argues strongly for this form of presentation and against reducing temperatures to sea level.

Governmental Climatology

Official Climatology: the Signal Service, 1870-1891. Meanwhile, in 1870, an official weather service had been established in the Signal Service of the Army. But there is continuity from the earlier organizations: Colonel (later Brigadier General) Albert J. Myer (1827-1880), to whom the organization of the new service was entrusted, had earlier served in the Medical Department. The new service took over entirely the system of voluntary observers that Henry had created, and the Smithsonian standards of instrumentation and observation. All records in the possession of the Smithsonian Institution were handed over to the Signal Service in 1873. The Signal Service was not instructed by law to concern itself with climate, but its responsibility to "commerce and agriculture" linked it with the tradition that had expressed itself in Blodget's and Henry's writing for the Commissioner of Patents before the federal Department of Agriculture was established in 1862. Climatologic papers appear early among the publications of the Signal Service: a set of maps of mean monthly temperature in 1881, and two years later maps and tables of monthly and annual precipitation /12/.

A new tendency appears in these publications: restriction of the summary to a fixed period and to the Service's net of stations, except for the use of records from Army posts in the work on precipitation. Data were now sufficiently abundant to obviate the need for scrapping together all available observations without regard to their homogeneity.

The Signal Service was assigned its largest climatologic task in its latest years as a public weather service, when it was called upon for information concerning the dry western parts of the country in connection with proposed federal legislation on behalf of irrigation. In the years 1888 to 1890 it supplied a series of reports, mostly by W. A. Glassford, an officer with much experience in the West, though on title pages generally credited to A. W. Greely (1844-1935), the last Chief Signal Officer before the weather service was transferred to the Department of Agriculture /13/. The most important of these reports are those on the Rainfall of the Pacific slope and on the Climatology of the arid regions. The latter contains extensive tables and maps of temperature and precipitation by seasons and critical months separately for Arizona, New Mexico, California and Nevada, Colorado, and Utah. An interesting innovation is a map of California and Nevada bearing generalized isarithms of annual evaporation in inches as measured with the Piche evaporimeter. The measurements used were a part of those on which Thomas Russell had based his evaporation map of the entire United States /14/ the map that E. N. Transeau later used in his attempt to express the moisture element in climate by the ratio of precipitation to evaporation /15/.

These reports present an estimate concerning the potentialities of agriculture in the dry West greatly different from those expressed by Blodget and Henry a generation earlier. The earlier authors thought that only a

small fraction of the dry area could ever be cultivated, since the supply of water for irrigation was obviously limited. Glassford, on the contrary, writing in 1890 with a background of experience in the West, estimated the area that could be cultivated far higher. In discussing Arizona he aimed to demonstrate "that the measured amounts (of rainfall) are sufficient to supply water for the irrigation of much more land than the acreage known to be available," a popular exaggeration against which John Wesley Powell argued in vain at an irrigation congress held a little later /16/. As for evaporation in its bearing on the use of water for irrigation, Glassford held it to be "relatively so small in comparison with the total fluid contents of the actual and projected storage basins that it may be economically disregarded as a vanishing quantity."

Official Climatology in the Individual States. In 1881 the second chief of the Signal Service in its capacity as a weather service, W. B. Hazen (1830-1887), initiated an expansion of the net of observing stations by soliciting the aid of the governors of all the states in organizing state weather services. His appeal met with great success. Before the national service was transferred to the Department of Agriculture as a civilian bureau in 1891, almost all the states had established such services, and the last one was organized in 1892. The state services were as a rule articulated with the state agricultural experiment stations, through which their observational data were frequently published. They were gradually absorbed by the Weather Bureau.

The state service that was conceived most broadly was that of Maryland, founded in 1891. Its first director, William Bullock Clark (1860-1917), conceived for it an exceedingly inclusive program, which was realized in a

series of impressive monographs. Its first Report that embodied this program, issued in 1899, contained "A General Report on the Physiography of Maryland" by Cleveland Abbe, Jr. (1872-1934), son of the scientific pillar of the Signal Service and the early Weather Bureau; "The Aims and Methods of Meteorological Work, Especially as Conducted by National and State Weather Services," by the elder Cleveland Abbe (1838-1916); "A Sketch of the Progress of Meteorology in Maryland and Delaware," by Oliver L. Fassig (1866-1936); and an "Outline of the Present Knowledge of the Meteorology and Climatology of Maryland," by F. J. Walz, who at the time was in charge of the Weather Bureau office in Baltimore. Walz's monograph contains by far the handsomest series of climatic maps issued by any state weather service: no other state had within its boundaries so competent a map printing firm as A. Hoen and Company of Baltimore. The Maryland service issued two additional Reports comparable in bulk and quality with the first. Volume 2, issued in 1907, is a monumental work on the climate and weather of Baltimore, by O. L. Fassig, a model of its kind; Volume 3, 1911, reflecting Clark's broad conception of the function of the Service, is concerned with the plant life of Maryland.

Nothing remotely comparable was achieved by any other state weather service. Their meager publications consist almost wholly of observational data, and the task of publishing these passed quickly to the Weather Bureau. When the services disappeared as administrative entities, they left behind them a mild interest in climate among the state agricultural experiment stations. Most of these institutions have issued publications on the climates of the respective states, few of which are more than bare tabular compilations of data. The authors of a few state climatographies have attempted to extract meaning from the material they have had to work with. Two that deserve

mention are an older report on Wisconsin /17/ and a more recent one on Florida /18/. The two latest ones issued by state agricultural agencies, on Kansas /19/ and Illinois /20/, make a more serious attempt than most of their predecessors to present the information on weather and climate that is significant for agriculture. In other states climatographies have been published by state geological surveys /21/ and state universities /22/. S. S. Visher's "Climate of Indiana" contains by far the most elaborate presentation of climatic data ever attempted for a state. On hundreds of tiny maps Visher has represented by isarithms many quantities computed and counted from the climatic record.

Official Climatology: the Weather Bureau (1891----). In transferring the national weather service to the Department of Agriculture, the Congress recognized what the public expected of the service. Among the duties with which the new bureau was charged was "the taking of such meteorological observations as may be necessary to establish and record the climatic conditions of the United States." Accordingly, climatology occupies a prominent place in its publications. Of its numbered series of bulletins, issued between 1892 and 1913, the one that still commands the greatest interest is number 36, written in 1891 but not published until 1905, by Cleveland Abbe, on the relations between climate and crops. This is mainly a digest of literature, but it contains a good deal of Abbe's own critical thinking. He was not satisfied with what he found in the literature, and appealed for a "climatic laboratory," using an expression uttered by A. de Candolle in 1866. Both he and de Candolle would welcome the realization of their wish in our time /23/.

In its quarto series of bulletins, designated by letters, the Bureau

summarized and refined the constantly more numerous and lengthening records of climate. In Bulletin C, 1894, the whole mass of records of precipitation to the end of the régime of the Signal Service was summarized in the most thorough presentation since the second edition of Schott's memoir. Bulletin D, 1897, bearing the indifferent title "Rainfall of the United States," is a critical supplement of its predecessor. Its author, Alfred Judson Henry (1858-1931), attempted in it to sharpen the concepts used in discussing precipitation. He was concerned with such matters as the length of record required to attain a dependable "normal;" the types of distribution of precipitation through the year; the amount of precipitation that falls during the crop-growing season, a motive that runs through all our later climatology; the secular variation of precipitation in different parts of the country; the synoptic conditions associated with rainy and dry months; the association of precipitation with the relief of the land surface; and the frequency of occurrence of intense precipitation.

The Bureau's most ambitious effort to summarize what was known of the climate of the country, except in purely tabular or cartographic form, Bulletin Q, appeared in 1906 under the title "Climatology of the United States," also by A. J. Henry. By this time official observations had been accumulating for a generation. The aim of having an observing station in each county, expressed by W. B. Hazen when urging the establishment of state weather services, had not been attained. But Bulletin Q has its tabular material arranged so as to refer to any county to a representative station. This tabular material, which includes more pertinent facts than are usually found in comparable compilations, occupies by far the largest fraction of the thousand quarto pages of the work. But what impresses one today is

Henry's introductory text. In this text Henry expressed his dissatisfaction with the organization of the material he was constrained to use. "The monthly means of temperature, pressure, the total monthly precipitation, etc," he wrote, "indicate in a general way merely the dominating influence of the month. In the final analysis, however, one should not fail to examine the daily weather charts, since similar montnly mean values do not necessarily represent one and the same type of weather conditions." And again: "It would also be a great help to the better understanding of seasonal variations in the weather if the usual statistics of temperature and rainfall distribution, amount of cloudiness, etc., were classified and arranged according to the several types of weather that prevail in the United States."

What Henry was asking for was thus a synoptic climatology. He could not give his presentation the form he desired, but he did what he could to give meaning to his maps by describing in synoptic terms and by illustrative weather maps the synoptic situations that are responsible for spells of typical and atypical weather. The categories of synoptic situations he envisaged as appropriate to the grouping of observations are those in which the weather is dominated respectively by a cyclone or an anticyclone, and possibly a transitional type. It is scarcely necessary to remark that Henry's appeal for a synoptic climatology had no perceptible effect. He would have had to invent a new routine for the reduction of observations, and this he did not do. The abyss between the "investigation of storms" and the handling of large numbers of observations so as to yield a "normal," which first opened in the Smithsonian Institution a half-century earlier, remained unbridged.

It is not practicable to enumerate here all the Weather Bureau's

lettered Bulletins. They provide a sound numerical basis for a climatology of the country, especially a climatology for the weather forecaster of the time: readily accessible means, computed for different units of time, with which current weather can be compared.

Bulletin W, originally entitled "Summaries of Climatological Data by Sections," is the one of the Weather Bureau's lettered series that has been known by its serial designation better than any other; in one of the three editions in which it has appeared it has for forty years been the standard source of climatic data wanted for any purpose. It is purely an assemblage of numerical data. The original edition summarized the record to about 1910, the later ones, respectively, to 1920 and 1930. The last edition no longer bore the serial letter, but its users have continued to call it "Bulletin W." That no later revisions have been made is sorely regrettable, since for later data one must go to the serial "Climatological data," which in recent years, with the addition of new material and the adoption of offset instead of letter-press printing, has become so bulky as to be the despair of librarians.

By far the best set of climatic maps prepared in the Weather Bureau was issued by a different bureau in the Department of Agriculture, the Office of Farm Management. These make up three parts of the fragmentary "Atlas of American Agriculture," published between 1918 and 1928 /24/. The main maps are on a generous atlas scale, 1:8,000,000, excellently printed, by the Geological Survey, in color on a base that bears a fair representation of relief. The preparation of the Atlas fell in a period when there was much interest within the Weather Bureau in statistical expressions of the probability of occurrence of given values of the climatic variables. This concern

is expressed in the Atlas by the inclusion of numerous maps of frequencies and probabilities as well as of means.

Although a shift in the demands made on the Weather Bureau led to its transfer from the Department of Agriculture to the Department of Commerce in 1940, it contributed much of the essential material to the Yearbook of Agriculture for 1941, "Climate and Man." Its contributions include not only papers by members of the Bureau, but also a summary of the climate of the United States, presented in both tables and maps, that fills nearly 600 pages. This is the latest general summary of the climate of the country prepared by an official agency.

Agricultural Climatology

Until the end of the nineteenth century, American concern with the relation of climate to agriculture contented itself with generalizations regarding the limits of possible cultivation of crops, expressed in terms of precipitation and temperature. In the meantime agricultural settlement had continued, and the available stock of crop plants, including an ever widening range of varieties of each crop species, had been tried out. The problem conceived by the climatologists of the middle of the century, to discover the adaptability to agriculture of the parts of the country as yet unsettled, was solved by trial, both by individual farmers and at the state agricultural experiment stations founded, with federal subsidy, in the last quarter of the century.

The information that Cleveland Abbe put together in his report on the relations between climate and crops was based mostly on laboratory rather than field experiments, and reflected European rather than American experience. But actual cultivation, whether experimental or commercial, provides

quantitative data on crops in the form of yield, and it was with yield that the results of climatologic observations came to be by preference compared.

The earliest procedure for making this comparison was the parallel plotting, on a scale of time, of yield and some climatic factor that might be expected to affect it /25/. At about the turn of the century, however, the techniques of statistical treatment of observational data underwent rapid development in England. W. N. (later Sir Napier) Shaw published a pioneer effort at correlating yield of wheat with precipitation in 1905 /26/. It was followed in 1907 by R. H. Hooker's exemplary investigation of a number of crops, which made use of the best contemporary resources of correlation statisitics /27/. Four years later the new procedure appeared in the United States, in the form of a rather tentative study by J. Warren Smith of the relation of yield of potatoes in Ohio to weather factors, in which Smith used simple linear correlation /28/. This was the first of a long series of studies, of many crops and all available climatic factors, that Smith carried out, in most of which he used linear correlation. His work culminated in his "Agricultural Meteorology," 1920, a most ineptly written and organized book. A paper by Henry Wallace that appeared in the same year as Smith's book /29/ represented a great advance over what had been done earlier, especially in the use of multiple correlation and the application of a critical attitude to the problem.

Meanwhile others entered the field opened by Smith: among them T. A. Blair, D. A. Seeley, and in particular J. B. Kincer, who succeeded Smith as chief of the Weather Bureau's Division of Agricultural Meteorology. Kincer's work, which extended over a period of fifteen years, is noteworthy for its flexibility and ingenuity. All these investigations proceeded from the

postulate of one or more critical periods in the annual cycle of the crop plant, at which it is particularly susceptible to adverse effects of weather. They applied all the resources of Pearsonian statistics, but with only indifferent success. The latest name to be mentioned is that of W. A. Mattice, who after repeated applications of the best statistics available took leave in 1931 of this species of investigation, to which so much labor had been devoted. "The weather in its effect on agriculture has been scrutinized from afar," he wrote, "as through a long-range telescope, but very little has been accomplished in pursuing the microscopic detail necessary for a complete understanding of the underlying principles involved in plant growth. . . To enable us to know just how the weather is affecting a crop at any time. . . we need accurate and comparable data of weather and crop progress, with the details of various weather phases and of crop developments from planting to harvest accurately observed and recorded on the ground /30/." A program of precisely this sort has been undertaken, with corn, at Iowa State College, but has been in progress too short a time to produce results as yet.

A new epoch in the statistical treatment of the problem of crops and climate opened with the publication, in 1921 and 1924, of R. A. Fisher's masterly study of the yield of wheat on the famous Broadbalk plots at Rothamsted /31/. The method Fisher devised made it unnecessary to seek by trial hypothetical critical periods in the annual cycle of the crop plant. Instead, it provided a continuous measure, in the sense of the familiar coefficient of regression, of the influence of a climatic factor on yield. The first application of Fisher's method in the United States was apparently not to crop yields, but to the growth of trees and range grasses /32/. When it finally came to be applied to crops, those who used it were no longer

men of the Weather Bureau, but statisticians of the Department of Agriculture, to whom the problem was not one in natural science but rather abstract arithmetic /33/. A later paper emanating from the same group, however, goes beyond its predecessors by extending the method to measure the joint effects of temperature and precipitation on yield /34/. It represents the most original American work to date in the application of the newer statistics to the relation of climate to the yield of crops.

Statistical Treatment of Climatic Data

Aside from correlation statistics, which find their principal use in applied climatology, statistics occupy a central place in the interpretation of the climatic record itself. In the earlier history of American climatology, little attention was paid to the statistical qualities of the record. C. A. Schott, who brought to his climatologic work the habits and methods established by long experience in the reduction of observations in another field, is the one conspicuous exception.

Examination of time series in climatologic data has been continuous since more than a few years of observations were accumulated. Most collations of data for this purpose have aimed at no more than a graphic demonstration, with or without some sort of smoothing, of the fluctuations recorded. The vast amounts of arithmetic labor expended in the effort to find periodicities may be ignored. The study of sequences in various units of time has led to recognition of a certain amount of persistence, easily recognized and measured in units of days /35/, at some places even in successive years /36/. Interest in the persistence of departures from long-term means was stimulated by the occurrence of successive years of drought in the 1930's /37/ and by the general rise of winter temperature in the past 60 or 70 years. /38/. It is

not to be expected that such persistence as exists can be put to any appreciable use in forecasting for future years, but it poses a problem that insistently demands investigation. How provocative it may be is indicated by H. C. Willett's far-reaching generalizations concerning persistence in climate through periods longer than that spanned by the record of instrumental observation /39/. Although statistical tests for persistence in time series are available /40/, they have not been systematically applied for the purpose of determining the coherence or incoherence of the several parts of the United States in the fluctuations of climate. Such statistical investigations of the record would be a valuable complement to the studies of fluctuations in the general circulation by synoptic methods that have been pursued so intensively /41/.

Frequency distributions of climatologic observations, or, more often, the return intervals of given values, the reciprocal of probability when, as in climatic data, the individual vales of a variate pertain to units of time, first became of concern to hydraulic engineers. R. E. Horton wrote in 1913 /42/ that he had used expressions based on probability, "in some instances the ordinary Gaussian law and in some instances developing special probability curves, formulas, and diagrams," since about the beginning of this century. Two articles, by Allen Hazen and Thorndike Saville, published in 1916, recommended the application of probability to precipitation /43/. Both used the normal frequency distribution without questioning its applicability. Hazen's article was accompanied by a map of the United States that showed by isarithms the coefficient of variation (standard deviation expressed as a percentage of the mean) of annual precipitation. This map has often been referred to in the technical literature, even since the appearnace of a

later map of a closely related quantity, mean deviation expressed as a percentage of mean precipitation /44/.

Variation in precipitation has attracted more attention and invited more work than any other climatic statistic. It has usually been conceived as dispersion about the mean, but in one investigation, by B. M. Varney on precipitation in California /45/, it was handled as change from year to year ("variability"). Varney evidently did not know that variability is functionally related to dispersion in a random distribution, and so missed the opportunity of comparing his results with the results of chance sequence. Most authors have been content to use such an expression as Hazen computed in 1916, in spite of the evident dependence of the numerical value of the coefficient on the value of the mean, so that it displays a range of numbers running in the opposite sense from mean precipitation. V. Conrad /46/ has attempted to avoid the absurdity involved in the approach of the coefficient to infinity as the mean approaches zero, by fitting an empirical equation to the coefficients computed for a large number of stations. He obtained an expression for the coefficient of variation as a function of the mean, according to which it approaches the value 73 percent as the mean approaches zero, instead of infinity. Such a result is scarcely convincing, since as the mean approaches zero any measure of variation should also approach zero.

The problem of expressing the dispersion of values of precipitation in units of time about their mean thus remains to be solved. The achievement of a satisfactory measure of dispersion might hasten the disappearance of the often repeated dogma that precipitation is most variable in dry climates; a dogma that has no firmer basis than what is obtained by computing the coefficient of variation. This measure of dispersion is appropriate to series

in which dispersion both upward and downward is unlimited, but wholly inappropriate to a quantity such as precipitation, the scale of which is closed by zero in one direction.

The treatment of asymmetrical frequency distributions in climatic data appeared relatively early, in one of the many articles on the statistical handling of data that were published in Monthly Weather Review between 1916 and 1930 /47/, but has never become general. Hydraulic engineers began to work with skewed distributions at about the same time; Pearson's flexible Type III distribution was formally recommended to them in 1924 /48/. Frequency of occurrence of floods has since been taken by E. J. Gumbel as a starting point for an improved statistical procedure /49/, which has possibilities of applications in climatology that are as yet unexplored. Still more recently Pearson's Type III curve has been used for expressing the probability of weekly precipitation, in an investigation of drought in Iowa /50/.

A minor revolution in the handling of masses of observations has been effected by the introduction of punched cards and machines for sorting them. First applied to climatic data in the United States by the Weather Bureau in the 1930's, the use of punched-card methods was enormously expanded during the second world war. A brief account of this growth, with citations of literature, has been given V. Conrad and L. W. Pollak in the second edition of "Methods in Climatology;" and W. C. Jacobs has described the applications of the procedure made by the Weather Service of the Air Force /51/. The characteristic products of the punched-card technique, aside from the traditional sums and means, are frequency distributions within categories into which the data may be broken down; and in particular frequencies of associated values of different categories, such as temperature or precipitation with

direction or speed of wind. One product, to which Jacobs gives appropriate prominence, is a practical synoptic climatology, long asked for but never before realized. A few products of the card-sorting machine published since the second world war may be noted: a presentation of data relating to airports that closely resembles the war work described by Jacobs /52/, and application of the procedure to agricultural climatology /53/, and a bulky compilation of data for a single locality, Washington, D. C. /54/.

The record of statistical treatment of climatologic data in the United States is thus fairly good. If it invites any general conclusion, it is that too few of the persons working with climatologic data have had a creative knowledge of probability and the statistical procedures founded upon it. Hence too many of the good studies published have remained little more than demonstrations, examples that have not been followed.

Non-Governmental Climatology

Members of the national weather service have always found outlets for their writings outside official publications. The public, indeed, has normally looked to them for articles and books on weather and climate intended for general information. Such a book was A. W. Greely's "American Weather," 1888. It contains the first general set of climatic maps of the United States based on uniform official observations. Historically it is of interest in that it sets an example in organization that was largely followed in R. DeC. Ward's "Climates of the United States," published a generation later.

It is to academic institutions, however, that one has a right to look for the best scientific work; and in climatology the record of American universities is meager. The older academic tradition is well represented

by Elias Loomis (1811-1889) of Yale, who in addition to his many studies in synoptic meteorology compiled the first map of isohyets of the earth /55/. But academic climatology has no continuous tradition in the United States; instead, it is dominated by one figure, Robert DeCourcy Ward (1867-1931). Ward was the first, and for many years the only, professor of climatology in an American University; and none of the few that have arisen later approaches him in national and international prominence.

Ward's scientific preparation was gained at Harvard, under William Morris Davis, and his whole career was spent there, from his appointment as instructor in meteorology (changed to climatology in 1896) to his death. Of his copious writings only his books can be cited here.

Leaving aside his early manual "Practical Exercises in Elementary Meteorology," the first of these is his translation of the first volume of Julius Hann's "Handbuch der Klimatologie" /56/. Ward made no slavish attempt to reproduce Hann's words in English. He divided and rearranged Hann's material so as to give it a better articulation. He omitted passages and inserted new ones to give the English-speaking reader illustrations from places nearer home than were Hann's examples. He carried out all this work of adaptation unobtrusively, so that the book reads smoothly. Of Ward's translation it may be said, as of extremely few translations, that even for one who reads German easily the translation may be preferred to the original.

Some of Hann's ideas, as they appear in the opening pages of this book, can be identified in Ward's later, original writings. The following are the most important: "Climatology is essentially...descriptive in character"... "In climatology...those meteorological phenomena become the most important which have the greatest influence upon organic life. The importance of the

different climatic elements is therefore determined from an outside standpoint." "Climatology is thus seen to be a branch of knowledge which is in part sub-ordinated to other sciences and to practical ends...This point should be borne in mind when we treat climatology as a science auxiliary to geography."

These ideas articulated closely with certain concepts current at the turn of the century regarding the relation of life, and particularly human life, to nature, which have been subsumed under the term "environmentalism." Ward's teacher, Davis, when he turned from the problems of physical geography that he ordinarily dealt with and contemplated mankind on the earth, floundered in environmentalistic quicksand. N. S. Shaler, Davis's teacher, based a good deal of his sincerely humane thought regarding the problems of society on the same derivative of social Darwinism. It occasions little wonder, therefore, that Ward's next work, "Climate, Considered Especially in Relation to Man," first published in 1908, has an environmentalistic orientation. It is discursive rather than systematic, and accords with contemporary tendencies in academic geography in the United States rather than with the contemporary state of the physical sciences.

Ward's "Climates of the United States," 1925, is a much more substantial work, but retains a good deal of the same tendency. The first group Ward addresses in his preface is "teachers and students of geography." He "endeavored to make the presentation vivid by frequent references to the human relations of the various climatic elements and phenomena." Most of the content of the book, as of "Climate," had appeared earlier in the form of articles in journals, but in their collected form they constitute a much more tightly organized whole than the earlier work. Though Ward made full use of maps of means of the climatic "elements" (indeed, the book could

scarcely have been written without the maps recently published in the climatic sections of the Atlas of American Agriculure), Ward made a strong effort to take account of the synoptic aspect of climate. But, like A. J. Henry before him, he was unable to devise any method of articulating weather with climate. A decade earlier /57/ he had appealed for the treatment of climate by synoptic rather than time-units, and had indicated by a citation that he had read how Köppen had solved this problem in the early 1870's /58/. Yet neither then nor later did Ward arrive at any better way of discussing weather climatologically than by reproducing graphs of the change in weather during a representative sequence of days.

It is remarkable that Ward's "Climates of the United States," admirably organized and written as it is, offers little or no intellectual stimulation to the reader who approaches it only a quarter-century after its appearance. The reason is not merely that the revolution in synoptic meteorology that was under way when it was issued has been completed. It is rather that the book displays no questioning, no doubt, no consciousness of problems still to be attacked. It has one lasting value: its copious bibliographic footnotes. The student of the history of climatology in the United States scarcely needs to go beyond these footnotes and Ward's bibliographic articles cited in them for a guide to the literature published before the date of the book.

The last large work that bears Ward's name, the sections on the West Indies and the United States and Mexico in the Köppen-Geiger "Handbuch," published after Ward's death, contains work by too many hands to be representative of his authorship. Most of what is recognizably his had appeared earlier in his work on the United States. The reader who knows his other works is not astonished to learn that the extensive tabular material and the

admirable series of maps the work contains were not compiled and drawn by Ward, but by or under the supervision of C. F. Brooks.

The changing tenor of intellectual life has made another Ward impossible. No one born in the present century could attain a comparable level of learning and literary skill and at the same time complacently accept an essentially verbal climatology only loosely articulated with other aspects of the science of the atmosphere. One must suspect that the popularity of climatology in departments of geography in our universities stemmed largely from Ward's example at Harvard. Ward's books, used as undergraduate textbooks, were "easy," and deliberately in harmony with much instruction in geography. He had translated from Hann the statement that "climatology presupposes a knowledge of the most important teachings of meteorology," but his books demanded of their readers little of this knowledge. In many departments of geography, familiarity with the more exacting phases of meteorology came to be looked upon as superfluous, and students were offered courses in climatology without being required to have any such familiarity.

Neglect of the significance of contemporary advances in other phases of the science of the atmosphere for the understanding of climate is characteristic of our climatologic literature, both regional monographs and textbooks, in the third and fourth decades of this century. This shortcoming was in part compensated by a greater willingness to wrestle with masses of numerical data than Ward displayed. But Ward's example provided no guidance toward the discovery of a philosopher's stone that would transmute the base data of observation into the gold of physical generalization.

From the middle nineteen-twenties to the present time, much academic instruction in climatology has been focused on the classification of climates

and maps of climatic regions based on the classifications used. C. W. Thornthwaite has combined a review of the pertinent literature with a thorough (and adverse) criticism of the classification most frequently used, Köppen's of 1918 /59/. Much earlier, Ward had reviewed for his countrymen various proposed delineations of climatic regions, but none of these took root. The wide adoption and imitation of Köppen's classification when it became known in the United States in the nineteen-twenties undoubtedly resulted from the abandoment by American academic geography at about this time of its earlier environmentalism in favor of an intense concern with "regions." Maps purporting to show the distribution of types of climate fitted easily into the thinking reflected in this orientation. Much effort was expended in tracing in greater detail the boundaries of climatic regions, especially within the United States, shown on Köppen's small-scale world map, and in modifying his definitions so as to discover better boundaries between these regions than his original ones.

Thornthwaite's has been the most powerful voice raised against the uncritical application of Köppen's classification. More than a decade before the date of the article just cited, he had published his own general classification of climates, which grew out of his dissatisfaction with the Köppen classification, in particular with its delineation of the dry climates /60/. The most impressive monument of Thornthwaite's classification is an elaborate atlas issued by the Department of Agriculture /61/. It shows the distribution of the types based on Thornthwaite's distinctions of humidity for each calendar year and crop season of a forty-year period. No other document of our climatologic literature presents so effectively as this atlas the fluctuations of the moisture element of climate in the middle region of

The same primary concern with temporary or permanent shortage of water marks Thornthwaite's second attempt at a classification of climates, published in 1948 /62/, in which they are distinguished by the balance, in the course of the year, between precipitation and a quantity he calls "potential evapotranspiration," the amount of water that would be lost in unit time from the surface of the land if the cover of vegetation were transpiring it at the maximum rate permitted by the prevailing climatic factors, primarily insolation and temperature.

Our most important general treatise since Ward's death is Helmut Landsberg's "Physical Climatology," 1941. It represents a welcome protest against the trend that Ward established, but is not sufficiently comprehensive to rank with the best works of the past. V. Conrad's "Methods in Climatology," 1944 and 1950, reflects its author's European background rather than the growth of climatology in America. Much of this book is concerned with statistical techniques; but better ones than are described in it are currently in use here /32, 34, 49, 50/.

Beginning about 1930, a number of our universities and technologic institutions have inaugurated curricula for the technical training of meteorologists. These institutions are the most important centers of investigation of the atmosphere in the country. Their curricula demand a new kind of academic climatology, which has not yet emerged; it is evident that it must be far different from Ward's or one organized about a classification of climates. One full-sized textbook of climatology /63/ has come out of a department of climatology in a technical institution, but it does not reflect much serious thought on the part of its authors concerning the appropriate

content of a climatology to match modern meteorology in general.

From one theoretical viewpoint climate signifies the mean state of the atmosphere, a norm with which any instantaneous state can be compared. Landsberg has provided a specimen of that kind of climatology /64/, a concise and workmanlike job, the essential feature of which is a series of 29 maps of the earth. The mean state of the atmosphere represents a state of equilibrium with respect to many processes of flux and exchange: exchange of radiation among the earth, atmosphere, sun, and space; exchange of angular momentum between the surface of the earth and the atmosphere; flux of heat from low latitudes to high, in equilibrium with the balance of radiation; and balance of precipitation with evaporation, to name a few. The condition of equilibrium is the starting-point of many investigations of these processes /65/.

So far as one can see at present, however, many of the phenomena of motion in the atmosphere that are seen on the weather map and that are responsible for weather and its changes must still in the future, as in the past, be investigated empirically; that is, by synoptic methods. A particularly enlightening use of synoptic methods having climatologic significance is seen currently in the section on monthly weather and circulation published in Monthly Weather Review beginning with the issue for January, 1950. Maps of departure of monthly means from long-term means have been published in the Review for many years; but only recently has a method been devised whereby these departures can be referred to some more fundamental variable. This variable is the anomaly of mean circulation in the lower middle troposphere /41/. As in most investigations of climate, the month is somewhat too long a period to be as synoptically homogeneous as is desirable; but even within

this unit of time the anomaly of circulation at the 700-mb. level provides more insight into the fluctuations of the familiar aspects of climate than has been available heretofore.

Outlook

The most impressive contributions being made to climatology in the United States at present are thus coming from those who are working intensively on the true constituent elements of climate, the constantly changing states of weather recorded on synoptic maps. Their work is welcome after a long period in which the relations between weather and climate received only perfunctory recognition. It is concerned with "causes," as William Morris Davis used that word. As for "consequences," the other member of the alliterative antithesis Davis was fond of using, it is evident that any investigation must be highly specific, that procedures must be designed with the elaborate attention to detail that has long been familiar in the laboratory. Some aspects of the turnover of energy and water at the surface of the earth, such as the loss of water from the ground that Thornthwaite has long been concerned with, or the exchange of energy between the atmosphere and the surface of the sea investigated by Jacobs /65/, may be handled by means of conventional observational material. But the relations of organisms to climate present far more difficult problems. F. W. Went /23/ has shown what elaborate precautions must be taken if even the simpler reactions of plants to climate are to be defined quantitatively.

It can be foreseen that the solution of any problem in applied climatology in the future must involve special instrumentation and extremely detailed observations through a period of time long enough to sample a good range of weather. Mattice knew that twenty years ago /30/. Then, in the

most fortunate circumstances, ordinary climatologic observations may be used for extrapolation to other places and times. It is not to be expected, however, that circumstances will often be so fortunate. For general observations of weather, primary dependence will be placed on the regular stations established for synoptic purposes. The net of voluntary observing stations, introduced by Joseph Henry at the beginning of the period under review here, will lose the primary importance it has had so long.

It is to be hoped, however, that the time-honored system of voluntary observers will not disappear. Its disappearance would signify a great cultural loss, a part of the cultural impoverishment that goes with the excessive specialization of our times, in which people are alienated from techniques and modes of thinking not associated with their daily work. Though the scientific significance of his observations may decline, the voluntary observer should remain for his value to the community, especially in the country and the small town where the sense of neighborhood is not yet lost. The tradition of the scientific amateur, on which Joseph Henry depended for the initiation of a net of observing stations in the early days of the Smithsonian Institution, has never been strong in our country. But to the extent to which it survives in the voluntary observer it should be fostered. And perhaps there is a possibility of a climatology parallel to the rigorous numerical climatology with which this chapter has been mainly concerned: a natural history of climate. The rhythm of the seasons echoes deeply in our literature and folk-traditions. In the interpretation of this rhythm, in the communication of insights that are better expressed in words than in equations, the climatologist has a role to play, along with the amateur of plants and animals and the literary artist. These formulations,

no less than algebraic ones, can make the dry bones of climatologic tabulations alive.

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GEOMORPHOLOGY

Background Statement

Geomorphology is a study of the geometry and geology of the visible surface of the earth. It is composed of many parts which fall under the main heading of descriptive, dynamic and applied geomorphology. This definition and the development of these parts is the product of trends derived from applications of Huttonian and Kantian philosophies as introduced into America by Lyell and Guyot. They led to the development, late in the 19th Century, of two classsical schools of geomorphology. One of these, founded by T. C. Chamberlin, was chiefly concerned with glacial stratigraphy. The other, founded by W. M. Davis, was chiefly concerned with the genetic description of landforms. Divergent lines from these schools have led to the development of applied geomorphology, particularly with respect to human geography.

The most recent development has been the growth of climatic geomorphology, particularly with respect to arid and periglacial regions, under the leadership of Kirk Bryan. This development was part of an episode of increased activity in geomorphology. Today the science is more vigorous than at any other period in its history. Much still remains to be done. More applications present themselves than ever before. It seems that only adverse economic conditions or adverse governmental policies could halt or reverse this trend.

Definitions and Classifications

Definition: the name, geomorphology, is derived from three Greek words: geo (earth), morphos (form), and logos (discourse). It thus implies that the subject concerns itself with the configuration of the landscape and is a geometrical study. In practice, however, it has been found impossible to explain the origin or predict the properties of the geometric features of a landform

without a recognition of the geologic materials which lie immediately beneath the surface. Surface geology is therefore of primary concern to geomorphology. Hence one finds included in textbooks of geomorphology and in the writings of geomorphologists such topics as lithology, rock weathering and continental stratigraphy.

Geomorphology has also inherited, both in university teaching and in the preparation of scientific reports, certain related subjects. These are valid individual topics worthy of standing alone. However, they are essential to the geomorphic argument and, until separately developed, must be fostered. Such topics, which vary from one university or research organization to another, include ground water, fluvial hydrology, continental stratigraphy, pedology and paleoclimatology.

Geomorphology has, in fact, come to include surface geology and surface geologic process. The consideration of the earth's surface, its description and its genesis, not only permits but demands a consideration of the immediately underlying materials. Such a development, as will be shown below, was inevitable from the outset. Geomorphology may therefore be defined as the study of the geometry and geology of the earth's surface.

Structure

The structure of geomorphology is outlined below in Table 1., in which topics are suggested under each heading. Here it will be seen that the subject may be interpreted as made up of three major components: descriptive, dynamic and applied geomorphology. All are not equally developed, for descriptive geomorphology is the oldest branch; dynamic geomorphology is rapidly becoming a distinct subject; but applied geomorphology is new, unorganized

and incompletely developed. Attempts are still being made, by trial-and-error, to discover the fields where geomorphology can contribute most effectively.

In common with the general history of scientific thought, as it is represented in American science, geomorphology has revealed a five-stage sequence of events. They are:

1. Random collection of facts
2. Description and classification
3. Generalization and laws
4. Prediction and application
5. Disruption and specialization

The present development of geomorphology is concentrated in stages two and three with traces of development easily found in all other stages. Thus the major component parts of geomorphology outlined in Table 1 correspond to stages two, three and four respectively of the historical sequence.

Table I

Structure of Geomorphology

I. Descriptive Geomorphology (geomorphography)
    A. Regional Geomorphology
        1. Landform type (Physiographic provinces)
            a. shields
            b. old mountains
            c. young mountains
            d. intermontaine basins
            e. interior plateaus
            f. coastal plains
        2. Geologic type (Structural regions)
            a. plains and plateaus (simple structure)
                interior plains
                plateaus
                coastal plain
            b. mountains (disturbed structures)
                folded mountains
                dome mountains
                block mountains
                complex mountains
            c. volcanoes and related forms

3. Climatic type (Morphogenetic regions)
   a. glacial
   b. periglacial
   c. boreal
   d. maritime
   e. selva
   f. moderate
   g. savanna
   h. semi-arid
   i. arid

B. Comparative Geomorphology
   1. Physiographic comparison
   2. Structural comparison
   3. Morphogenetic comparison

II. Dynamic Geomorphology (geomorphogeny)
   A. Systematic Geomorphology
      1. Fluvial geomorphology
      2. Solution geomorphology
      3. Marine geomorphology
      4. Glacial geomorphology
      5. Periglacial geomorphology
      6. Eolian geomorphology
      7. Volcanic geomorphology
   B. Climatic Geomorphology
      1. Morphogenetic process
      2. Polygenetic sequence

III. Applied Geomorphology
   A. Natural Sciences
      1. Geology
         a. geologic mapping
         b. geologic history
      2. Pedology
         a. soil erosion
         b. soil genesis
      3. Botany
         a. plant geography
         b. ecology
      4. Climatology
         a. microclimatology
         b. mountain climatology
         c. air mass climatology
   B. Social Sciences
      1. Archeology
         a. age determination
         b. geographical reconstruction
      2. Human Geography
         a. land utilization
         b. transportation geography
         c. urban geography
   C. Engineering
      1. Civil Engineering
         a. soils
         b. railroads and highways
         c. waterway
         d. hydrology
         e. irrigation
         f. erosion control
      2. Military Science
         a. terrain analysis
         b. trafficability
      3. Mining
         a. placer deposits

<u>Descriptive geomorphology</u> has been dominated by the followers of Davis who endeavored to find a basis for a geomorphic description of the earth. Regional geomorphology has thus been the major kind of descriptive geomorphology to be developed. Today the geographer may select from three different types of regional description: the physiographic province; the structural region; and the morphogenetic region. The physiographic province (see Fenneman 1931, 1938) is based upon the general aspect of landforms. The structural regions, as developed from the teachings of Davis by Johnson and Lobeck (see Lobeck, 1939), are dependent upon geologic structure and the assumption of a close correlation between landforms and geology is either made or implied. The morphogenetic regions (see Peltier 1950) are based upon the assumption of a close correlation between climate, weathering products and erosion features.

<u>Comparative geomorphology</u>, as a kind of descriptive geomorphology, is not greatly developed. Its growth will, however, continue as the increasing body of knowledge make complete regional descriptions and analyses overwhelming. The body of fact related to each region is growing so rapidly that it is becoming less and less feasible to comprehend and review all parts even of the United States. This development toward comparative geomorphology will be further enhanced by the growth of systematic geomorphology and its recognition of regional variation in geomorphic process.

<u>Dynamic geomorphology</u> has developed as a study of surface processes together with their products. Its development in America has been irregular and dependent upon the fortunes of the different schools of thought. Thus glacial geomorphology, pursued by the followers of T. C. Chamberlin, and the fluvial geomorphology of Davis and his school have been strongly developed. Marine, solution, eolian and volcanic geomorphology are poorly developed in

comparison. Interest in periglacial geomorphology has recently been aroused by Bryan and his students. Activity in this field appears to be increasing rapidly both in private research and under such governmental agencies as the Alaska and Permafrost Section of the U. S. Geological Survey and the Snow, Ice and Permafrost Research Establishment of the Corps of Engineers.

Applied geomorphology has been a recent development in response to the demands of the other arts and sciences (see Bryan, 1950). In some instances (see Table 1), as in geography or geology, the demand was so great that these fields developed geomorphology as an integral part of themselves. In some other instances, as in pedology and archeology, applications were developed by geomorphologists. The greater body of applications has, however, been developed by people who usually consider themselves outside of geomorphology. In applying geomorphology, they have acted in the interest of pedology, botany and other fields.

Methods

The unique techniques of geomorphology are mostly office and laboratory techniques. The field techniques and other laboratory techniques are borrowed, with varying degrees of modification, from other disciplines. The scale, or absolute size, of the landform is not always an important consideration in studies of pure geomorphology, but is very important in applied geomorphology. Thus, those investigations which are concerned with geomorphic process or with dynamic models as a basis of analysis are primarily interested in shape or form. Concern for absolute size is subordinated. However, when features of constant size, such as roads, buildings, airports and harbor facilities, are to be related to landform the absolute size of

the landform becomes of major importance. For example: a fault scarp may be expected to exhibit the characteristic features of fault scarps, indicative of their genesis, irrespective of size. However, the difficulty of climbing over this scarp, as expressed in the metabolic costs on the man, or of building a road over it, as expressed in cost of construction or man-hours of work, may be expected to vary significantly with the absolute size of the landform feature.

The office and laboratory techniques consist both of various methods of descriptive geomorphology based upon previously collected data, usually either in the form of contour maps (see Salisbury and Atwood, 1908) or aerial photographs (Smith, H. T. U., 1941) and of the methods of dynamic geomorphology based upon scale models. The purely descriptive methods consist of topographic classification and description of the type illustrated by Johnson (1933) and Zernitz (1932) and of such operations upon contour maps as the development of maps of relative relief (Smith, G. H., 1935) or of slope classes (Wentworth, 1930; Veach, 1935). These operations are designed to condense or summarize the data presented by the contour map. They always tell less than the map itself, but are sometimes a quite useful though laborious means of expressing simplified relations. Other office methods of descriptive geomorphology are analytical in type. They consist of the projected profile (Barrell, 1913), topographic cross section (Guyot, 1849), generalized contour map (see Horberg, 1946) and the reconstructed contour map (Hewett, 1926).

These commonly encountered analytical techniques may be arranged in a systematic fashion to provide a standarized procedure for the office analysis of landforms. Such a procedure is an excellent way of discovering problems and even of postulating answers. It may even provide a geometric analysis

and a geometric argument, but, because it does not take the evidence of surface geology into consideration, the results are not conclusive.

The laboratory techniques in dynamic geomorphology are centered about the dynamic model (see Hubbert, 1938). These have successfully treated problems in river action (Friedkin, 1945), wave action (Keulegan, 1948), wind action (Shoews, 1932), frost action (Taber, 1929), talus behavior (van Burkalow 1945), sheet wash (Lowdermilk and Sundling, 1950), and doubtless many others. These studies have admirably provided a rational means of analysing geomorphic process and a qualitative means of predicting the rate of change in surface features resulting from these processes.

It is however, well recognized by workers in this field that very severe limitations are put upon the translation of measurements made upon the dynamic model into values of the scale of nature. There are, in addition, the limitations which arise in transferring observations made upon a closed and controlled system to the open and uncontrolled natural environment. The controlled experiment may be repeated, but in nature there may be instances in which similar results are obtained by the interplay of different assemblages of forces and materials. Furthermore, geomorphic quantities and forces are now loosely defined. They can not be expressed in dimensional form. Certainly a redefinition of geomorphic terms must precede any rational quantitative analysis in geomorphology. At the present time a quantitative consideration of geomorphic features can only be carried out by graphical or statistical methods. In the interpretation of these results dynamic models serve chiefly as dynamic analogs.

The field techniques of geomorphology are almost entirely the techniques of surveying, pedology and geology. They consist of the construction

of contour maps and topographic profiles with the aid of alidade, transit or less elaborate reconnaissance equipment, the field measurement of geomorphic process such as velocity of stream flow, velocity of shore currents, rate of sheet erosion and the rate of gully development, the construction of the geologic and soils maps, the geologic section, the soils profile and the lithologic description of the surface materials. Geomorphology has, in addition, contributed one unique technique, the construction of the geomorphic map (Alden, 1918). It has been widely used in Pleistocene studies. Its application, following European practice, is now spreading to studies of unglaciated regions.

Historical Sketch

Early Development

American science, particularly natural science, is divisible into three major periods: one, an age of natural philosophers, which prevailed prior to the early 19th Century; another, an age of naturalists, which dominated science from the early 19th to early 20th centuries; and the third, the current age of specialists, which came into being about the beginning of the 20th Century. In all of these periods American science was profoundly influenced by European thought.

The science of geomorphology in the United States is an outgrowth of the age of naturalists. Almost from its birth this subject has grown along two separate but complementary paths. One, which was eventually to mature into dynamic geomorphology, began with the introduction of the Kantian geography of Ritter and von Humboldt into the United States by Guyot in 1849.

American textbooks in geology which appeared between 1840 and 1890

were strongly influenced by Lyell's work. Their preoccupation was thus with minerals, rocks, fossils and geologic history. However, many of the current concepts of geomorphic interpretation, such as those related to diastrophism, the work of rivers and the work of waves, are traceable to Lyell. He argued, from the Huttonian doctrine of uniformitarianism, that:

> "The geologist who assents to the truth of these principles will deem it incumbent on him to examine with minute attention all the changes now in progress on the earth, and will regard every fact collected respecting the causes in diurnal action, as affording him a key to the interpretation of some mystery in the archives of remote ages." (Vol. 1, p. 166)

Thus dynamic geomorphology has come to be included, with other aspects of dynamic geology, in physical geology for the light it might throw upon the origin of geologic features of the past.

Prior to 1850, and indeed for a long time thereafter, American geography was dominated by the encyclopedic type of descriptive geography of Jedidiah Morse. This he defined (Morse, 1819) as:

> "a branch of mixed mathematics (which) treats of the nature, figure and magnitude of the earth; the situation, extent and appearance of different parts of its surface; its productions and inhabitants." (Vol. 1, p. 9)

Morse and his followers were chiefly interested in mathematical geography and in the compilation of useful and interesting information of the lands and peoples.

Geomorphology became a part of American Geography following the introduction of European concepts by Guyot (1849). In a sense Guyot was a predecessor of American systematic geography just as Morse may be taken to have set the pattern for American descriptive geography. Guyot defined geography by saying:

> "It should not only describe, it should compare, it should interpret, it should rise to the how and wherefore of the phenomena which it describes. It is not enough for it coldly to anatomize the globe, by merely taking cognizance of the arrangement of the various parts which constitute it. It must endeavor to seize those incessant mutual actions of the different portions of physical nature upon each other, of inorganic nature upon organized beings, upon man in particular, and upon the successive development of human societies, in a word, studying the reciprocal action of all these forces, the perpetual play of which constitutes what might be called the life of the globe, it should, if I may venture to say so, inquire into its physiology." (p. 21)

Guyot saw geography from the viewpoint of a naturalist and conceived of it as a study of the natural history of human phenomena.

Landform thus became introduced into American geography as the stage upon which the human drama was played and geomorphology became important because it influenced the occurrence and characteristics of other geographic features. American geography which developed during the last part of the 19th Century was, as a result, a curious mixture containing the mathematical geography of Morse, the geomorphology of Guyot and the climatology and anthropology of both of these authors together with the descriptive geography of Morse.

Two Classic Schools

Two main lines of geomorphic thought have grown from the philosophies of Lyell and Guyot. It was inevitable that one of these lines should be intimately attached to geology and be essentially historical in its objectives and that the other be attached to geography and be chiefly aimed toward applications and interrelations. In practice neither extreme has been closely followed, but, from 1890 to 1940 American geomorphology was dominated by two schools of thought. One of these was founded by T. C. Chamberlin and the

other by W. M. Davis.

Chamberlin's interest was essentially historical and his point of view may be interpreted as the direct outgrowth of the influence of Lyell upon American science. He and his followers concentrated upon the study of glaciers, glacial deposits and past glaciations. This interest, on the part of Chamberlin, was probably an outgrowth of his early interest in cosmogony.

This school developed a system of glacial mapping, based upon geomorphic features, and the sub-science of glacial stratigraphy. Their activities led to the extensive mapping of glacial deposits throughout central and eastern United States. Their task was formidable, but their work has been productive as may be seen by a glance at the Glacial Map of North America by Flint and others (1945).

From time to time divergent lines of the Chamberlin school appeared. Thus Salisbury and Atwood pioneered in the rational interpretation of maps (1908) with notable results. Flint, on the other hand, has pressed the exploration of glacier physics until he has developed America's closest approximation to a school of glaciology. There have also been signs of the development of divergent schools of geographic thought. Thus, for example, the school begun by W. W. Atwood was a school of regional physiography in which the configuration of the landscape was interpreted as a supporting or limiting influence on the human drama (Atwood, 1945). It is still too early to predict the future of these divergent lines, but is clear that they are needed and should be supported.

Although Davis was not a student of Guyot, there was a similarity in many of their ideas as though the younger man had gained from the teachings

of his older contemporary. Like Guyot, he was a geographer who was competent as both a meteorologist and a geologist. To many of his contemporaries he seemed to preach geography but to do geology. This arises from a misunderstanding of Davis' objectives and the conditions under which he worked, (see Davis, 1909) strove to devise a system of descriptive geomorphology which would have an intrinsic meaning. The descriptions would thus carry implications which could be used further in deriving general principles concerning the relation between landform and human activity. The explanatory or genetic description seems the most promising. Even though Davis called for the extension and refinement of this descriptive system his writings do not indicate that he considered such descriptions to be the ultimate objective. Davis' followers have tended to follow more closely his example in studies of genetic description and classification of landforms than his pleas for geographical integration with other natural and social sciences.

The great achievements of Davis and his followers were the areal description of the United States compiled by Bowman (1911) and Fenneman (1931, 1938), the systematic description of shorelines (Johnson, 1919, 1935), and the systematic study of soils (Marbut, 1913). However, Davis' cyclical interpretation of landforms and his recognition of the complex history of erosion and uplift of mountains captured the imagination of geologists and geographers alike. Suddenly it became possible to postulate a geomorphic history from an otherwise meaningless mass of hills and valleys. Many people yielded to the temptation to make such postulates; too often there were those who did not tarry to prove them, thus it is, after volumes have been written on peneplains, that we are nearly as ignorant of the details of their properties as the day the peneplain was described by Davis.

The blind following of a leader can not be expected to bring about great progress, but here we have evidence that the disillusionment and strong reaction which often follows such a practice may destroy or obscure even the valid principles of the master and retard the development of such principles and practices as are needed. Thus, following an initial surge of activity and enthusiasm in Davisian geomorphology between 1905 and 1920, there was a doldrum period of about 10 years in which the geographers turned to human geography and geologists went in search of oil. Davisian concepts had become so obscured by inept followers that they seemed unreal. The Davis school was kept alive during this time, primarily by Douglas Johnson and his students.

Recent Development

A strong revival of interest in geomorphology began about 1930. This was marked by a sharp increase in the number of papers on geomorphic subjects to about 100 papers a year, an increase of graduate students in geomorphology, and a gradual increase in the number of universities which offer the subject. There is no evidence that the peak of this rise has yet been reached. The revival of interest was probably the product of the sequence of war-inflation-depression for during and immediately following a war the attention of geographers is held by governmental activities and by large classes in geographical subjects in universities and the attention of geologists by the problems of economic expansion. Thus research in such aspects of pure or applied science as geomorphology seems to be born in adversity; productivity seems to vary in some direct relation to the value of the dollar.

This period of increased interest in geomorphology was also marked

by the appearance of the Bryan school of thought. Its philosophy is intermediate between that of the Chamberlin and Davis schools for it has borrowed heavily from both as well as from the followers of Albrecht Penck in Germany. Bryan strongly supported Davis' system of descriptive geomorphology, but argued that one cannot understand the surface except through an understanding of the surface materials. He further argued that, because nearly all existing surfaces came into being during Pleistocene time, genetic geomorphology could not be divorced from Pleistocene stratigraphy.

The major achievements of this school were in climatic geomorphology, particularly in arid (Bryan, 1922) and periglacial (Bryan, 1946) regions, and in the applied fields of civil engineering (Bryan, 1929), soils (Bryan and Albritton, 1943) and archeology (Bryan and Ray, 1940; Hibben, 1941).

Current Trends

Present Situation

A new era, dominated by younger men who for the most part are products of the 1930-1942 period of revival, may be supposed to have begun about 1950. This is a reflection of the very small number of men who entered geomorphology between 1920 and 1930. The present group does not have either the guidance or the restrictions of their teachers. Under such intellectual freedom, in the virile field, one may anticipate the development of several different and divergent fields of thought. Thus we may expect the entire field of geomorphology and its borderline topics to be covered more effectively than would be done by careful following of already established schools.

By 1950 American geomorphology had reached a stage characterized by the achievement of a reasonably thorough regional description of the country

and by the general statement of many outstanding problems. Several basic concepts had been formulated. Among these were the concepts of base level, erosion cycle, nick points, retreat of slopes, regimen of streams, climatic fluctuations and polygenetic surfaces.

The cream may have been skimmed from the top, but the discovery of principles and the proof of hypotheses, with all of the attendant drudgery remains. Not a single topic has been exhausted. In most instances the work which must be done is on an enlarged scale and requires much more detailed observation than previously. The greater detail of observation, newly available data, and the guidance of new concepts do, however, justify the re-examination of many classic areas and problems.

Descriptive Geomorphology

Descriptive geomorphology has been dominated, until recent years, by the methods of regional description applied by Bowman (1911) and Fenneman (1931, 1938). Their descriptions of the United States comprise one of the great achievements of American geomorphology. This type of study however, is not wholly suited to application to detailed studies of land use, transportation or other large-scale topographic features. As a result a second trend, one of empirical description, has become prominent. This trend, which was led by Wentworth (1930), Guy-Harold Smith (1935) and others reached a peak of development in the land classification studies of the U. S. Department of Agriculture. It has been particularly valuable as an expression of a need in geomorphic description which goes beyond the Davisian system. It has made it clear that a purely descriptive system, which can be used before a geomorphic analysis is complete, is badly needed. It has similarly made clear the demand for landform description in much greater detail than that used by such

regional geomorphologists as Fenneman.

Any consideration of land surfaces, beyond a crude classification, will show that the differences between surfaces are due to differences in the agents or regimes which produced them. Thus a descriptive classification which emphasizes minor forms and which is based upon the conditions of development is most likely to meet the requirements of both the geographers and many others who have found applied geomorphology useful.

These conditions, on a gross or regional scale, are met by the newly-developing field of climatic geomorphology. Here geomorphic features are related, through the formative processes, to the climatic regime under which they were produced. Soil features and biological elements are also related to climate. Thus geomorphology may be related to the other elements of physical geography through the common denominator of climatology. The recognition of climatically determined morphogenetic regions does not imply discard or replacement of either the physiographic provinces or the structural regions for a different order of geomorphology is treated. It does, however, permit more detailed studies in comparative geomorphology following a rational pattern and the recognition of evidences of a complex climatic history. It provides for a system of analysis and regional comparison of slopes, soil producing (pedogenic) regions and erosional phenomena. These may prove to be useful in applied geomorphology.

The system of climatic geomorphology may eventually be extended to include microgeomorphic studies. However, at the present time a system of microgeomorphic classification based upon the attitude of the surface, the nature of the subjacent materials, and the agent which produced the surface seems both most applicable and most promising.

Dynamic Geomorphology

<u>Fluvial geomorphology</u> has been studied in the mountainous regions and alluvial valleys of both humid and semi-arid climates. Mountainous regions have been studied by Davis (1889, 1911), Blackwelder (1915), Johnson (1931), Bradley (1935, Atwood (1938) and many others. Studies of alluvial valleys are exemplified by the work of Lawson (1915), Bryan (1923), Russell (1936) and Putnam (1942). These, and other, broad studies have served to clarify, to some degree, the Davisian concepts of the erosion cycle and the characteristics of the peneplain. Corollary to these studies were those of drainage pattern interpretation pursued chiefly by Johnson (1931) and of pediments as studied by Bryan (1922). As a result of these studies some limited areas have become classic for their treatment, and others nearly as promising have been relatively ignored. These classic areas are the Lower Mississippi Valley, the Colorado Plateau, the middle Rocky Mountains of central Colorado, and the northern Appalachian Mountains.

Fluvial geomorphology of alluvial rivers as exemplified by the studies of Bryan (1923), Russell (1936), Putnam (1942), the Army Engineers (Fisk, 1945) and the Soil Conservation Service (Brown, 1944) has aroused increasing interest. It is likely that it will not only persist as a major part of fluvial geomorphology, but will exceed all other aspects in its practical importance.

Recently there has been increased interest in slope morphology as reflected in the studies of the Soil Conservation Service (see Bennett, 1933) and in the work of Sharpe (1938) Horton (1945), Strahler (1950), and others.

The major problems which students of fluvial geomorphology face today concern the relationship between fluvial features and other environmental

conditions. One of these problems concerns the relation between discharge, stream load, gradient and channel characteristics; another concerns the effect of changes in climatic regime, vegetation cover or sea level upon stream flow characteristics. The most pressing need, however, is for a classification of rivers, or of parts of rivers, which is related to their characteristics of flow, erosion and sedimentation.

The studies of solution geomorphology have been concentrated upon cave studies following either the approach outlined by Davis (1930) or that of Swinnerton (1932). Most attention has been given to cave description and the smaller cave features. Relatively little has been done on the relation of caves to regional features and relatively little has been done concerning the topographic features of solution landscapes.

Marine geomorphology surged suddenly ahead during the war 1914-1918. This surge reached a climax in the 1920's when Johnson published his two volumes on shorelines (1919, 1925) in which he applied the observations of Gilbert (1890) and European geologists to an analysis of shorelines in general. Perhaps Johnson overwhelmed the field for there followed a period of distinct inactivity notably broken by Antevs (1929), Cooke (see Cooke, 1936) and the Beach Erosion Board. A second surge of interest accompanied the war of 1939-1945 and its amphibious operations. (See Anonymous, 1944; Bigelow and Edmondson, 1947). The products of this period are illustrated by the laboratory experiments of Keulegan (1948).

Marine geomorphology, including shorelines, is a broad, relatively undeveloped frontier of dynamic geomorphology. Almost every aspect of the subject is in need of further study. No attempts at comparative or regional consideration of shorelines have been extensively carried out. The

geomorphology of undersea areas, particularly that of shallow waters, is greatly in need of study as possible aids to navigation or to the study of fisheries.

Glacial geomorphology is commonly divided into studies of continental glaciation and of mountain glaciation (see Flint, 1947). Both branches have advanced rapidly during the past 60 years. This has largely been brought about by the efforts of the Chamberlin school. Two of the most notable developments in continental studies are the growth of the concept of glacial recession by stagnation and the growth of the concept of separate and distinct glacial stages composed of sub-stages (Flint, 1941). These concepts have been challenged by Longee / /. Efforts of the followers of the Chamberlin school have also led to the development of a standard Pleistocene chronology in the upper Mississippi Valley and its extension westward (e.g. Flint, 1949) and eastward (e.g. MacClintock and Apfel, 1944). These efforts have made the upper Mississippi Valley and adjacent Great Lakes region the classic area in American glacial geomorphology (see Alden, 1918; Alden and Leighton, 1915; Kay and Apfel, 1929; Leverett, 1899, 1932; Leverett and Taylor, 1915).

The developments of the immediate future, in continental studies will probably include an exploration of the implications of these two concepts. One line of investigation may relate to the influences of meteorological conditions and subglacial surfaces upon the manner of glacier movement and type of recession. Another line will probably extend the climatic interpretation of the Pleistocene and result in a division of the pre-Wisconsin glacial stadia into sub-stages. This will further lead to a recognition of buried loess deposits and their climatic significance.

The recent studies of mountain glaciers and their deposits have been

dominated by problems of glacier regimen (Dyson, 1948), climatology, and glacier mechanics (Demarest, 1942; Sharp, 1948). These, however, are intimately related to the interpretation of the Little Ice Age of 1650-1850 described by Matthes (1941). The general retreat of American glaciers since 1900 provides an inviting group of problems involving meteorological and hydrological observations about the glaciers and observations of changes in shape and size of the ice. Meanwhile the problem of correlating the Little Ice Age and earlier substages with the features of lands not covered by this ice (as was done in part by Bryan and Ray, 1940) remains active and pressing.

Periglacial geomorphology of the Pleistocene in the United States is still in its infancy. The fact of a periglacial regime during the glacial episodes of the Pleistocene is only now becoming generally recognized. Thus the implications of the periglacial concept have only scarcely been touched upon. The more spectacular forms of frost-produced soils are now becoming abundantly reported (Denny, 1936; Sharp, 1942; Smith, H. T. U., 1949). The less obvious forms will be recognized in time. The frost-produced rubbles, by their association with stream terraces of unglaciated valleys, demonstrate the fact of periglacial alluviation (Peltier, 1949). A similar association with dune sand, ventifact pavement and loess mantle is leading to the recognition of wind action as an important feature of periglacial conditions (Hobbs, 1931; Smith, H. T. U., 1949). The immediate problems include that of the distribution of frost-produced features and periglacial deposits in the United States as well as the variation in size or type of these features from place to place.

The phenomena of current periglacial processes have, on the other hand

been known for a long time through the studies of the Alaska Branch of the U. S. Geological Survey (e.g. Leffingwell, 1915; Cairnes, 1912; Eakin, 1916). Their study is now being actively continued by the Alaska and Permafrost Sections of the U. S. Geological Survey, the U. S. Bureau of Plant Industry, Soils and Agricultural Engineering and many individuals (e.g. see Journal of Geology, Vol. 57, No. 2 (1949) which is entirely devoted to articles on periglacial topics). It is still early to predict developments, for this field is still in the early stages of observation and classification. It is, however, a topic in which the student can scarcely avoid a discovery.

Eolian geomorphology is another underdeveloped branch of American geomorphology. Most of the observations on dunes have been studies in sedimentation. However, dunes have been classified (Melton, 1940; and Bagnold, 1942) and their form has been related to the supply of sand and the velocity of wind. Hack (1941) has studied the relation between plants and dune form. Huffington and Albritton (1941) have further recognized buried soils and multiple generations in the sand dunes of Texas.

Studies of loess have advanced much more rapidly. Loesses of Nebraskan, Kansan, and Illinoian age as well as at least four Wisconsin loesses occur in central United States. Guy D. Smith (1942) has proven earlier contentions that these loesses are derived chiefly from the large alluvial valleys. Thus the regime which produced alluviation must also have led to loess development. Recent studies by various writers have demonstrated the existance of thin bodies of loess, often containing pebbles intermixed by frost-heaving, throughout northeastern United States.

The available knowledge of eolian deposits is now being compiled upon a single map by a committee under the leadership of James Thorp and

H. T. U. Smith. The needs for further exploration, correlation and interpretation in eolian geomorphology are quite apparent from it.

Since I. C. Russell wrote on the volcanoes of North America (1897) studies in volcanic geomorphology have been neglected. Those studies which have been made concerned separate areas. They do not lead to comparative studies. Among these studies are those of W. W. Atwood, Jr. (1935) and Nichols (1946). Thus the future for studies of volcanic landscapes in the United States is great, but such studies must begin with the elementary matters of description and classification.

Applied Geomorphology

Attempts, with varying degrees of success, have been made at the application of geomorphology to related subjects (see Table 1). The oldest and most often used applications are found in geology, pedology and human geography. The newer applications in the other fields are of equal or greater potential importance.

The earliest applications in geology were made, following Lyell, in the reconstruction of conditions of sedimentation. They are well illustrated by Barrell (1907, 1908). Another equally important application has been found in the field mapping of geologic units and structures. This application is based upon the assumption of correlation between surface form and surface geology. It is well illustrated by Salisbury and Atwood (1908). Other applications have related to the interpretation of Cenozoic History (e.g. Atwood and Mather, 1932) and unconformities (e.g. Sharp, 1940).

The application in pedology (Bennett, 1933) have been largely related to soil erosion and soil conservation. This application was recently

greatly increased by the establishment of the Soil Conservation Service. The second major application of geomorphology in pedology relates to soil genesis as illustrated by Leighton and MacClintock (1930) and Bryan and Albritton (1943). This application, long generally recognized, has been rapidly expanded during the past decade. This is exemplified by the current cooperative program between the U. S. Geological Survey and the U. S. Bureau of Soils.

Applications in botany are largely indirect applications of geomorphology by way of pedology. They are problems which relate to the interpretation of changes in plant associations or to the interpretation of forest history and forest site. Development of this field has not been extensive and has been carried out mostly by plant geographers and ecologists (as for example Cooper, 1935, 1937 and Raup, 1945, 1946).

Similarly the applications of geomorphology in climatology have largely been made by climatologists. These applications have related to mountain climates (see Lansburg, 1941), the effects of mountains and lowland swamps upon air mass properties (Conrad, 1942) and the effects of topographic features in microclimatic analysis (Howell, 1949).

The applications of geomorphology in social science, as illustrated by studies in the United States, have been concentrated in the field of human geography where a time-honored association has existed since the days of Guyot. This has arisen, at least in part, from the recognition that certain similar geomorphic landscapes may be characterized by correspondingly similar botanical associations and such cultural characteristics as route, settlement and land-use patterns. Thus, in Massachusetts, one finds the closest affinities of the sand plains of Cape Cod in the sand plains of the Connecticut and Merrimac Rivers. Similarly, the low-lying sandy Atlantic Coastal

Plain of New Jersey and Maryland, cut by swampy embayments, has become associated with the development of peculiar cultural patterns which extends across political and historical boundaries and sets the region apart from the adjacent hilly region of the Piedmont. No doctrine of geomorphic determinism is here presented, but merely an illustration of the way in which geomorphology, inter alia, may influence the growth of patterns in cultural geography. Other examples may exist, but the applications and significance of geomorphology in this field have been very modest.

The associations, such as described in the foregoing examples, are realities, but their analysis and interpretation is often complex. In many instances the association is not fully understood. It seems likely that more detailed studies of small areal units must be made before the principles, essential in the interpretation of the larger regions, can be discovered. Such intensive studies in the topics of land utilization, transportation geography and settlement geography have seemed, in this connection, at the same time both fruitful and most promising.

In <u>land utilization</u> studies in the United States, where suitability of the land for cultivation or for building construction is important, such elements as soil type, drainage and dissection and slope are significant. In transportation geography, which is related to geomorphology in matters that reflect cost of construction and maintenance, such elements as slope, surface dissection, foundation conditions and surface drainage are significant. Thus surface materials, drainage, slope gradient and relief, insofar as they relate to cut-and-fill requirements, are significant in discovering the potential relative accessibility of any place. The principles involved in these relationships must be well understood before the effect of geomorphology upon

the other phenomena of human geography can be properly evaluated.

Recently geomorphology has been of increasing service to anthropology particularly in the fields of prehistoric anthropology and archeology. Although there has always been some connection between these subjects, and archeologists have always been willing to invite the assistance of surface geologists, it has only been within the past 20 or 30 years that their questions of age, correlation and environmental reconstruction could be met. The studies of the Sandia Cabe (Hibben, 1941), the Lindenmeier Sité (Bryan and Ray, 1940), the Hopi Sites (Hack, 1942) and the Boylston Street Fish weir (Johnson, 1949) exemplify the various types of archeological problems to which geomorphologists have, in recent years, been able to contribute.

The principal applications of geomorphology to the various branches of engineering, particularly civil engineering and military science, arise largely from the different approach of the two fields. Geomorphology is a natural science based upon rational argumentation whose objective is first the natural history of geomorphic phenomena and second the prediction of the occurrance and characteristics of these phenomena. Engineering, by virtue of its preoccupation with design and construction, cannot wait on theory. Its very nature requires its methods to be empirical. However, engineers have generally been quick to apply principles of prediction whenever they were available. The field of geomorphology can be of greatest service to the engineering profession as a source of additional principles for the estimate and prediction of geomorphic features.

In the field of geomorphology applied to civil engineering at least as much geomorphic research has been produced from the engineering laboratories as from laboratories of geomorphology. Noteworthy examples of

such research may be found in the publications of the U. S. Army Engineers Experiment Station, the Beach Erosion Board, and the Scripps Institution of Oceanography. Thus in the fields of hydrology, soils, and soil erosion there have been two separate and almost independent lines of development with the bulk of the work being done by engineers (for example; see Hydrology Handbook by Bernard and others, 1949).

The geomorphic applications to military science are essentially special cases of the applications to human geography and to civil engineering. The terrain studies included in the JANIS reports, and in other joint or combined reports of the last war, were essentially special cases of transportation geography and settlement geography. The applications of geomorphology to these fields, as outlined above, have applied equally well here.

Other applications in the field of applied science and engineering exist. Their possibilities are infinite but their importance, in the total realm of human existence, are not great. Somewhere a gold prospector may use a geomorphic principle in "tracing down" a vein or finding a placer. An oil man may use other simple and obvious principles in locating a "structure." Elsewhere a home owner may consider the "lay of the land" before digging a well or a farmer may plow his field in contours. These are matters of common knowledge and serve as examples of the way in which geomorphic principles have crept into everyday life. They are not examples of great scientific triumph. They are proof that the demand of scientific principles, expressed in common terms, is in no sense restricted to the economically or politically articulate. It must, for this reason, fall to the scientist to evaluate the demands of his people, as well as of his problem, in order to determine how best the public good will be served.

The Future

The trends of science reflect the historical currents of the time. Today we witness a contest between empiricism and rationalization, a contest between experimental science and natural science, just as we recently observed the impacts of the contest between spiritual and material motives upon the realm of scientific thought. The future trends of any branch of science, such as geomorphology, must follow the dominant pattern.

The dominant trend in science, today, is toward specialization. Perhaps this is a definitive characteristic of our society. However, there is a point of diminishing returns in scientific specialization. A man can be too narrowly trained. The specialist may come to lose the flexibility of thought essential in applied fields. The reaction against specialization is reflected in the trend toward general education. This reaction has been paralleled by recognition, in some quarters, that nature must, in the final analysis, be studied in the field where various branches of science bear an inseparable relation to each other. It is, however, still too early to predict which vector, the trend or the reaction, will become dominant.

Perhaps this will be determined by society's demand as reflected in the policies of both the government and private institutions and in the applications of the various arts and sciences. In response to the peculiar demands of wars and industrial expansion the entire field of science is now, during the period of 1945-1960, under considerable pressure to develop the applied branches. The danger of going too far in this direction to the point of drying up the supply of basic principles has become broadly recognized. Various groups and agencies have acted to thwart this trend as, for example the Office of Naval Research and Congress through the establishment of the

National Science Foundation. It is thus apparent that American geomorphology as well as other branches of American science is intimately bound to American society which will openly or indirectly determine its future.

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SOIL GEOGRAPHY

The soil is part of the environment of every place, just as is the climate. We study the geography of soils so that we can make predictions - predictions of what will happen if we use the soil of particular places in particular ways.

The Necessity For Soil Classification

To understand the soils of different places well enough to predict their potentialities we have to classify them and make maps to show where the different kinds are found. No description of the soils of a place, not based upon mapped classes of soil, is likely to serve this purpose well. Therefore the story of the geographic study of soils is very largely the story of the development and use of a workable soil classification.

Any classification of soils well suited to making good predictions must be one which discloses, for each kind of soil, all of the attributes that will have an important effect on its behavior under use and the performance of different crops or structures upon it. Any soil has a large number of different characteristics which together determine its character and utility. The importance of any one of these characteristics depends upon the others with which it occurs in combination in a soil. Thus, to know that a soil has a loam texture is important, but if one does not also know whether this soil has a high water table, a shallow depth over an impervious layer, or a steep slope, one does not know enough about it to make many useful predictions. Therefore soil classification schemes which take account of only part of the soil's attributes however important these might be if other conditions were equal, are not generally worthy of use in geographic research.

Failure to grasp this rather simple principle has been the cause of more misleading characterizations of soils than almost any other single thing.

Evolution of Concepts in Soil Classification

Early concepts about kinds of soil. Farmers have used, no doubt since the beginnings of agriculture, local terms to denote different kinds of soil known to them, for example: black land, gumbo, hummock land, clay. While we recognize such classifications as being of almost no use in systematic geographic research, early classifications by geologists were scarcely better. Actually, soils have been studied outdoors - in contrast to the laboratory - a relatively short time. For a long time study of soils was principally by chemists, influenced by Liebig's theory of plant nutrition, which said, in effect, "the soil is like a bank - you put in what the crop takes out." We recognize some validity in this theory, but we now know that we cannot predict all the potentialities of a soil by chemical analysis in the laboratory any more than we could determine the characteristics of a river by testing a sample of its water.

It was no doubt natural, before people began to seriously study the soils themselves, to classify soils in terms of the rock underlying them. So we have had soils classified according to the age of the underlying rock formation, as Silurian soils or Carboniferous soils; according to the method of accumulation of the parent rock material, as residual soils, or transported soils; or according to the kind of rock, as granite soils or limestone soils.

However, a few geologists, notably Hilgard, began to notice that soils had some characteristics that could not be attributed to the kind of rock they come from. He remarked /6/ on the prevalence of lime in soils of the western semi-arid region, regardless of whether they came from limestones or acidic rocks. He understood the principle /6/ that once you have studied the geographic distribution of soils with different characteristics, you are in

position to select samples for analysis with some assurance that the samples represent more than the spot where they were collected. This principle we recognize today as one of the important reasons for mapping soils.

Shaler /11/ was another geologist who perceived that the soil was something more than weathered rock. He recognized the biological factor in soil formation, and lamented the lack of a systematic study of soils in relation to geology, chemistry, and botany.

The beginning of soil mapping. In 1899, the United States Government began a survey of the soils of the country, in which the different kinds were shown on maps. With many persons working at soils outdoors and sorting them into kinds to be shown on maps, the observations of relationships between the soils and the rocks, the vegetation, the drainage and the relief or lay-of-the-land multiplied enormously. A great number of different kinds of soil were mapped, and these were described and distinguished in terms of some of their own characteristics, as well as of the parent geological material. Yet, it was apparently at least 12 years before anyone discovered that soil types could be grouped according to anything but geology.

For example, in 1909, the U. S. Department of Agriculture, Bureau of Soils, published in its bulletin "Soils of the United States" /13/ a map dividing the country into 13 provinces. One of these provinces was called "glacial and loessal." Within this "province" were included both the steep, shallow, stony soils of the Adirondacks and White Mountains and the deep, level to gently sloping, highly fertile soils of the Illinois and Iowa prairies. It is hard to imagine any soil region map that would have as little relation to the actual characteristics of the soil of the country. It is quite evident that this map resulted from an effort to fit soils into preconceived notions

of how they should be classified, regardless of how these notions agreed with on-the-ground observations of the soils themselves. It is simply another instance of how even supposedly scientific people cling to concepts to which they have been conditioned, in face of evidence that suggests new concepts.

George N. Coffey's Interpretations. In 1912 the Bureau of Soils published the doctoral dissertation of George N. Coffey, /2/ who for the previous 11 years had worked in the Soil Survey as field mapper and inspector of mapping. This thesis "A Study of the Soils of the United States," was recommended for publication by Milton Whitney, then Chief of the Bureau of Soils, with the disclaimer that it was done to offer the scientific world a contribution of soil science, without endorsing the scheme of classification employed or the conclusions presented. Reading Coffey's work today we recognize the good sense and scientific soundness of it. He advanced the idea of a soil classification system based on all the important characteristics of the soils themselves, rather than on any single feature, and went as far as he thought he could in suggesting a broad grouping of United States soils based on this principle. His work is a classic and a milestone in soil geography.

The Russian School and its Influence. Coffey made reference in his thesis to the work of the Russian soil scientists, Dokouchayev and Sibertsev, and may have been influenced by them in his own attempt at major soil groups. These Russian workers emphasized climatic influences in soil formation, and recognized broad soil zones, distinguished from one another by climatically-caused soil characteristics. K. D. Glinka, Director of the Agricultural Institute at Leningrad, reviewed and summarized the Russian soil scientists' theories of soil formations and classification in Die Typen der Bodenbildung /3/, published in 1914. The Russian workers noticed that the soils over large

regions had certain similar characteristics regardless of the kind of rock underneath. Noting the correspondence of these soil characteristics to cultivated regions they attributed them primarily to the climate.

In their view, only those surface materials that had remained in place long enough to show some of the characteristics impressed by the environment of that place were true soils. Fresh materials, such as that recently deposited by a stream, was not soil, but a mechanical deposit. Therefore, a soil when washed from a hillside and redeposited somewhere below would cease to be a soil and become merely alluvium. Recent American literature of soil classification /1, 7/ has tended to reflect this point of view, but as a practical matter, all land areas have to be brought into the soil classification system, whether they are theoretically "true" soils or not.

Dokouchayev handled the problem of what to do with redeposited soils, in his 1879 classification, by calling them "extra normal" soils. Soils that have not been changed by dynamic processes other than soil-making processes he called "normal" soils. Thus, in order to account for all of what ordinary people consider to be soils, he had, in effect, to allow two definitions of soils in his scheme of things, one to cover all soils in the broadest possible sense, and one to cover those soils that had developed as a result of "soil" forming (environmental) processes. It would be easy to criticise this as illogical, yet we have to recognise that the processes of erosion and deposition are in fact also geological processes, and that the processes peculiar to soil formation are of the sort Kokouchayev so labelled. Glinka did criticize Kokouchayev's use of "abnormal," pointing out that such a soil could not exist in a natural classification system. He insisted that a soil transported to another locality is not a soil of any kind, but a mechanical deposit.

Sibirtseff, about 1898, presented a system of soil classification basically similar to Dokouchayev's, but containing some new features. The soils which distinguish the great soil regions that correspond more or less to climatic regions and reflect climatic differences he called "zonal" soils. But he also tried to place in his scheme those soils which, in all the zones, differ markedly from the predominant zonal character. These he separated into two broad classes: 1) "intrazonal," if their occurrence was limited to one zone (example: alkali soils occurring within soils of the dry steppes) and 2) "azonal" if they occurred irrespective of the zones (example: alluvial soils). With some modification this grouping corresponds to the highest category in the present American soil classification system, namely, the <u>order</u> /12/.

Glinka in "Typen der Bodenbildung" proposed a classification which, like those of the earlier investigators, emphasized climatically-induced soil groups All soils he broke first into two broad groups: 1) ektodynamorphic - those that owed their character primarily to external forces (principally climate), and 2) endodynamorphic - those in which the nature of the parent rock has influenced the character of the soil so strongly that it is not what one would expect from the climate under which it developed. Ektodynamorphic soils were subdivided into groups according to the relative amounts of moisture reaching the surface layers. One such group concluded wet soils, like peat; another the soils of semi-arid and arid regions. These groups were subdivided in turn according to: 1)major profile groups, 2) parent rock, and 3) mechanical composition (texture).

<u>Marbut and the Natural Classification System.</u> Dr. Curtis F. Marbut, in charge of the United States National Soil Survey from 1913 until 1934,

became acquainted with the Russian theories of soil classification and apparently found much in them that confirmed his own theories drawn from on-the-ground observations of many soil profiles all over the United States. He translated from the German Glinka's "Typen der Bodenbildung," /4/.

It is interesting to surmise why our now virtually international system of soil classification springs so largely from Russian and North American investigations, rather than from western Europe where farming is more intensive, and where one would expect the geography of soils to be more intensively studied. The soils of both Russia and the United States show striking regional characteristics, e.g., the dark colors of the steppe and prairie soils in contrast to the light colors prevailing in the timbered regions. Soil differences within a western European country were local differences related to the rocks. Broad regional differences related to climate were not so evident.

Marbut tried to see how well the Russian schemes of soil classification could be applied in classifying the soils of the United States into great groups. He concluded that the Russians emphasized climate too exclusively in their major grouping. He felt that a truly natural system of classification should be based on all the soil's characteristics, however they might have been caused.

American soil mapping experience suggested that vegetation, independent of climate, often had a profound effect on soil characteristics. The American prairies afforded the most striking example of this. In this region soils that had been under the natural tall grasses were markedly different than those under forest, and were separated from them by sharp boundaries that could hardly be ascribed to climatic differences. Russia had no great area comparable to the humid prairies of our Central States.

Marbut also stressed the factor of time in soil development. Clearly it takes time for environmental factors to affect the character of a soil. Material freshly deposited by streams, wind, or glaciers is quite different than it will be after it has lain in place for a long period. Hence you will find soils in all stages of development according to how long they have been where they are. "Young" soils, Marbut said, will express primarily the character of the geologic material; in "old" soils the characteristics acquired through environmental influence will overshadow those due to the parent rock. "Old" soils tend to have sharply differentiated layers or horizons, especially subsoil layers that are tight or slowly permeable, while "young" soils generally lack these features.

Topography (including drainage) affects the development of soil as a natural body, Marbut pointed out. Thus the five factors responsible for soil characteristics were climate, vegetation, parent rock, topography, and time.

The soil profile characteristics themselves, not the factors that produced them, were what Marbut proposed to use in classifying soils. His classification on this basis is contained in the Atlas of American Agriculture /10/.

A Soil as a Geographic Body. In more recent years we have paid more attention to the reality that a soil is not merely the successive layers of earthy material at a particular spot, but a natural geographic body with definite areal extent and surface configuration /7/.

Marbut dealt primarily with the medial profile of each soil type or group. But soils vary in a geographic continuum. Thus if we are to have classes or kinds of soil, they must be defined by ranges of characteristics, or sets of characteristics falling within certain limits. A kind of soil we think of as a little landscape (Fig. 1). Defined in this way a soil is not

separable from its surface configuration, which we now regard as one of its characteristics - an external one, as distinguished from internal ones such as structure.

Recognition of the geographic character of the soil type has helped us greatly in applying the results of laboratory tests and field plot experiments to farms and fields - the soil type tells us what area our sample or our field plot represents.

The Still-Developing System of Soil Classification

We have gone far toward devising a natural system of soil classification, e.g., one in which the classes are defined and distinguished in terms of their own natural characteristics. Yet the system is far from perfected. The soils of many parts of the world are still poorly explored and in large part unmapped. Soils are encountered every now and then that do not fit into any of the great soil groups previously recognized. This suggests that we shall find new members of this category for some time to come. Furthermore, research is constantly disclosing new relationships among soil characteristics that improve the basis of classification.

Present American theory and practice of soil classification are well summarized in a symposium published in the February 1949 issue of Soil Science /12/. Here are set forth the basic principles underlying soil classification; and the fundamentals of the American system of classification are outlined. They will not be repeated here.

Function of a natural soil classification. It will be profitable to consider why we stress the development of a natural classification of soils, for the reason is not well understood by some workers in agriculture and engineering and probably not by a good many geographers. Many such workers

appear quite content with soil classifications expressed in terms of the utility or performance of the soil, e.g., "corn" soils, meaning soils well suited to corn, or "plastic" soils or "first class" (or sixth class) soils (for agriculture, tilled crops, peanuts, irrigation, airports, or whatnot). Why is anything more necessary? Perhaps for a particular problem at a particular time no more would be necessary. But clearly we cannot afford to make a new investigation of soils each time a new problem arises. Suppose we have classified a particular soil as a third-class soil for cultivated crops? What does this classification tell us about it? Is it suitable for alfalfa? Does it need lime? Must it be leveled before irrigation? Can it be used "as is" for highway subgrade? Will it drain quickly after rains? Will it afford a source of gravel for road or building construction? Not one of these questions can be answered from the knowledge that the soil is third-class for cultivated crops. Identification of the soil in a taxonomic classification, on the other hand, discloses information about its character, which permits all these questions to be readily answered.

The need of taxonomy in soils is analogous to the need for it in botany. Knowing that a tree is a honey locust tells us its characteristics and utility, and the performance of its wood. Similarly, knowing that a soil is Tama silt loam, tells us its characteristics, utility, and behavior. Lacking a natural classification system, we would have to test every plant specimen, or the soil at virtually every spot, to predict its utility.

Taxonomy not enough. Obviously, however, the natural classification by itself does not afford enough knowledge to predict the capabilities of soils in particular places. To do that we must have knowledge, gained by experience or experiment, as to how the different kinds perform when used in given ways.

Again, this can be illustrated by a botanical analogy. We may be well able to identify the Virginia pine and place it in our taxonomic system. But until someone has tried to make pulp and paper from this tree, we do not know whether it makes good pulpwood or not. Once we have made pulping tests with samples of Virginia pine and found it suitable we can predict with some confidence that this species has good pulping potentialities wherever it is found. So it is with soils.

All this is to emphasize two important phases of the geographic study of soils: 1) mapping the soils to show the different kinds as defined in the natural soil classification system, 2) mapping interpretive classifications so as to show the potentialities of the soils for various purposes.

Classifying Soils to Show Use Potentialities

Interpretive Groupings. Given a map showing the soils of an area identified as units of the natural classification system, the geographer or other worker can prepare a great number of maps of the area, each showing the distribution of some one soil characteristic affecting land use, crops, farm practices, or engineering practices in some important way. For example, all the soils having poor drainage may be very easily delineated from those having good drainage. Similarily, all soils having gentle slopes can be separated from those having steeper slopes, all soils with root-hindering layers can be outlined, as can all those with bedrock at slight depth. However, the geographer or other worker skilled in interpreting the influence of soil characteristics upon the performance of particular crops or structures will not trouble to make maps of individual characteristics. Rather, he will consider the combined effect of all the characteristics of each soil upon its suitability for use and make his predictions accordingly. Indeed, if he makes maps

showing certain characteristics, but not all of those relevant to the problem, he may be unduly swayed by those he has chosen to map. The danger of judging a soil on the basis of one or two characteristics while neglecting others was pointed out earlier.

One important problem in soil geography is how to describe mapped kinds of soil so systematically that workers who need to appraise the suitability of soils for specific purposes can do so from the soil map and accompanying data, without a lot of research and interpretation on their own part. One device recently coming into use is the tabular summary of soil properties as a map accompaniment, an example of which is given in Table 1. This kind of table contains results of observations and interpretations by the field soil scientist, and greatly facilitates use and understanding of the soil map on the part of workers needing geographic information on soil properties and behavior. It seems likely that such tabulations will come into general use accompanying soil maps and that the number of properties and behavior characteristics to be so portrayed will be expanded, as experience and research disclose new facts about the different soil units.

Classifications predicting utility. More important than groupings which sort out and show distribution of soils possessing specified properties are those in which soils are classified according to productivity for particular crops, response to irrigation or drainage, erosion hazard under specified management, major use suitability, or general agricultural productivity (as related to, say, tax assessment). Such classifications can take many forms and can deal with an almost innumerable number of uses and practices, engineering as well as agricultural.

Much controversy has raged over the question of whether we need to

choose certain forms of land classification (in the sense of land-suitability-predicting) and apply them universally. Actually, a much greater problem is to secure recognition of the facts that 1) many land classifications can be derived by interpretation once the soils have been mapped and their characteristics and performance data tabulated and that 2) lacking identification of the kinds of soil, one is without any firm basis for land classification, and must rely on other evidence which may often be unreliable or of transitory value.

There is, indeed, need for many kinds of land classification, each to meet particular kinds of problems. Some will, according to the kind of problem to be met, depend on economic as well as upon physical considerations. But some will be soil capability classifications, in which the units of classification are the kinds of soil identified in the natural soil classification system. Examples of these are found in Soil Science, February 1949, pp. 141-150 /12/. The great mistake to be avoided is that of proceeding directly to conclusions about utility, without use of any system of taxonomy to which we may turn for basic data on soil characteristics when our conclusions have become invalid on account of changed economic circumstances.

Relating Soil Performance to Soil Classification. Gradually we are beginning to grasp the full significance of mapping kinds of soils as classified in a taxonomic system. Even now, many see nothing in it beyond a once-over-the-ground gathering of information about soils. This, important as it is, is only the beginning of the geographic study of soils. It is the framework on which we organize and apply geographically, our continuously increasing knowledge of the performance of soils. Our analogy of the Virginia pine and the pulpwood will help illustrate the point. Suppose the wood we

tested for pulping quality was simply wood of an unknown and unidentified species. Of what value would our findings be? None at all, until we had identified the tree species. The same with soils. If we carry on an experiment in a particular spot, where will the results have value? We do not know for sure that they will apply to any place except the plot where the experiment was done, until we identify the kind of soil. Then they will have value where-ever that kind of soil is found.

This simply means that an important part of the geographic study of soils consists of relating the results of experience and of experiments, to the kind of soils on which they were obtained. We can then classify results by kind of soil and build up information of great prediction value. Crop yields are one of the well-known kinds of performance data related to soils that have been collected and used in geographic prediction. In engineering we have only begun to recognize the potentialities of this principle and use it by classifying results of physical tests by soil types, so as to develop performance classifications of soils. /12 pp. 159-161/.

National inventory - what shall be its scope and level of detail? Implicit in a national soil mapping program is the idea of inventory - counting up to see what we have of different kinds. In a soil inventory, what should be the different kinds that we count up? We could, of course, add the acreages in the different types, series, families, great soil groups, and so on. But certainly people will expect more than this from a soil inventory. They will not be content with such facts as that we have 979,319 acres of Dillsboro silt loam. It seems plain that our inventory must count units in some kind of classification according to soil utility.

The natural soil survey program of the Department of Agriculture and

the State Agricultural Experiment Stations has not carried any standard interpretive classification in terms of soil potentialities or utility. It seems probable that any such classification made 40 years ago would now be obsolete in many respects due to the great changes in the production potentialities of some soils, resulting from changes in agricultural techniques. However, it may well be argued that the soil survey has completed enough work that classifications permitting inventory are now desirable. For reasons mentioned earlier, it is possible to develop such classifications from soil surveys already completed, although not in all the detail with the older maps that would be possible with more recent ones.

Soil maps have portrayed continually increasing detail through the years, in response to need. Field maps in farming sections are made on aerial photographs usually at a scale of about 1:15,840. Publication is very often reduced to a scale of 1:31,680, with some loss of detail through combination of areas. The published maps lose so much detail in this process that they are not generally considered suitable for farm planning, which must rely on the larger-scale field sheets. If the maps are to be thus generalized for publication, could they not be generalized much more, and still show enough for the uses not requiring full detail, thereby saving much publication expense? Should inventory data be in accord with the detailed field maps, or with the published maps? Is inventory really needed, anyway, except in broad terms? Could it be amply provided from a sample of detailed surveys representative of each important soil association area? What are the important categories to be used in a national inventory? These questions need careful consideration in a light of how different alternatives would serve the needs of different groups of users.

<u>Geography of Soil Patterns</u>. More important than inventory, however, is the importance of displaying the soil pattern and of predicting the fitness of enterprises that are governed by that pattern. All who have mapped soils in the field are aware of the complex intermingling of individual small bodies of different, sometimes sharply contrasting, kinds of soil. Figures giving total acreages of soils in different suitability classes, for an area or region, are seldom, in themselves, of great practical value. Small bodies of deep, level, fertile soils, interspersed through a matrix of rough, stony land may have scarcely any value for cultivated crops, while an equal acreage, concentrated in a few larger bodies might be highly desirable crop lands. Hence, both the characteristics of individual kinds of soil, and their geographic association in patterns, must be considered in geographic studies of soils looking toward prediction.

This would seem to require, in every area, highly detailed soil maps. In some areas, for certain specific problems such as highway design they will be necessary. But apart from mapping, which is designed to meet a problem known to require high cartographic detail, it is usually not practical to map out all the detail that one actually encounters on the ground. It is simply too expensive for the ends in view. What then, does one do?

Fortunately soils very commonly occur in patterns that are repeated again and again. Two or more types will be found in association in more or less characteristic proportions and characteristic landscape positions. The whole of an area possessing a characteristic pattern of associated soils we now call a soil association. Soil associations can be mapped and characterized as to the proportions and geographic arrangement of the associated soils. When the characteristics of the latter are understood, good predictions of

the use potentialities are possible. The detailed pattern of each soil association area is learned by mapping a sample of it. By this process much progress toward an understanding of soil potentialities of particular places can be made, short of mapping in extreme detail.

It can be seen that soil inventory could deal with soil association areas, placed as units in some use capability classification, rather than with the units of a highly detailed soil map. As a matter of fact, almost any soil inventory we can afford to make over a large area, will involve some generalization of the detailed distribution patterns we often find on the ground. It would seem better, in such an inventory, to recognize frankly that we are dealing with soil associations as units of mapping instead of treating each area generalized in mapping as though it consisted wholly of the predominant soil, as has often been customary in the past.

Mapping procedures for large regions lacking information. Many countries interested in mapping their soils would prefer a procedure by which they could get some useful information for all parts of the country, without waiting for the entire area to be covered by detailed mapping surveys. Such a procedure would have much merit and would be useful in any large region, such as Alaska, where there is little knowledge of the geography of the soils. Charles E. Kellogg, Chief of the Division of Soil Survey in the U. S. Department of Agriculture, visualizes a procedure to accomplish this end /8, 9/.

The first step in this process is making the best possible schematic soil association area map of the region or country, on a scale, say, of 1:1,000,000, utilizing any and all evidence there is, e.g., existing soil maps; maps of geology, physiography, relief, and natural vegetation; climatic data, and even notes of travelers. In view of the known facts that soils owe

much of their character to the rocks, climate, vegetation, and relief under which they have developed, it can be seen that if the geography of these factors is understood, fairly good general interpretations are possible of what soils may be found under different combinations of the factors.

The second step is to select sample areas representative of each of the broad soil association areas, and study and map the soils in detail, fitting them into the standard classification as far as possible. At the same time all possible information about the productivity, and response to various management systems, of the different mapped soils would be accumulated, and the best possible set of use and management predictions made for each. Farm advisers would be taught to recognize the different kinds of soils and become acquainted with their assets and limitations. In this way information developed in each sample area would have practical value throughout the soil association area of which it was representative, as agricultural workers would have learned to identify each of the important kinds and would apply to them use and management recommendations developed in the sample area.

The investigation in each sample area would, in effect, give an understanding of the pattern of soils throughout the soil association area. With knowledge of this pattern and the classes of soils in it, reconnaissance surveys could be used to revise the boundaries of the heretofore schematic soil association area map.

Detailed surveys would then be extended to other parts of the soil association areas in accordance with the importance of problems requiring them.

The merit of this scheme is that it gives agricultural research scientists and farm advisers a framework of soil classification that permits them to sort out results of experience and research according to kinds of soil

to which they apply, and thereby to fit in some degree, recommendations of use and management to soil character, in all parts of the region without waiting for detailed maps. This, of course, assumes their ability to learn to identify the different kinds of soil. The same principles would apply in gaining soil information for uses other than agriculture.

Full utility of soil classification will, in fact, not be realized until the ability to identify soils is one of the working tools of farm advisors and those engineers whose problems are related to kinds of soil. However, accurate mapping of representative sections in all important soil associations, by soil scientists experienced in soil classification is essential to widespread ability to identify, and is of great benefit elsewhere. On the other hand, even wealthy countries cannot afford to map the soil everywhere in the detail needed for intensive uses, such as building construction. So the necessity of soil identification remains, in spite of maps.

Progress in Soil Mapping

Approximately half the area of the United States has been covered by soil surveys made in enough detail to enable reasonable predictions of the potentialities of the soils. It has taken about 50 years to achieve this coverage (Fig. 2). At the present rate of coverage, more than this length of time would be required to complete the map of the country, except for the possibility that soils information from some of the unpublished conservation survey maps of the Soil Conservation Service can be used to construct soil maps with relatively little field work.

Many other countries have recognized the need for soil maps and made progress toward getting them. These include: Canada, Australia, New Zealand, Netherlands, Belgium, Portugal, Germany, United Kingdom, and the African Colonies of France, Britain, and Belgium, the Soviet Union, and others.

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HYDROLOGY

The field of hydrology may be considered as that part of physical geography concerned with the occurrence of water on the earth. An improved understanding, in quantitative terms, of earth-water relationships finds important application in physical geography. Geographers have usually dealt with water relations primarily in terms of climatology and geomorphology. They seldom considered hydrology specifically as a separate factor with which they were particularly concerned, inasmuch as water problems seemed to be adequately treated in the other disciplines.

It is the purpose of this essay to examine hydrology as it relates to geography, to note its relations to the other sciences usually considered basic to geography, and to indicate how recent developments and trends in hydrology impinge on the geographic field.

Scope and Development

The scope of hydrology is generally considered to be best expressed by the concept of the hydrologic cycle. In diagrammatic form, this concept has been presented in a large number of publications. It indicates that water precipitated from the atmosphere in part flows off the land and in part infiltrates into the ground, to return in part to the atmosphere. Contributions from both surface and subsurface water feed the rivers and thence the oceans. Infiltrated water contributes to transpiration, evaporation, and seepage to the ground water table. Transporation and evaporation provide the mechanism for return of water to the atmosphere to be reprecipitated, warm ocean surfaces, of course, providing the principal source for evaporation.

Various aspects of the hydrologic cycle - characteristics and processes concerning water in vaporous, liquid and solid states on both the earth and in

the atmosphere above the earth's surface – are considered from different points of view in the fields of meteorology, climatology and hydrology. Those pertaining specifically to water on the land surface and within he ground are included in hydrology. Hydrology treats of rivers, springs, snow fields, glaciers, floods and droughts. Likewise, it embraces study of processes such as transpiration, infiltration, evaporation, and sediment transportation.

A comprehensive review of the historical development of the field of hydrology is given by Meinzer /15/. In this connection, it is interesting to note that quantitative hydrology began in the seventeenth century with measurements of rainfall and river discharge in France. At that time it was first realized that rainfall is adequate to account for the flow of springs and streams, and that evaporation from the Mediterranean Sea is ample to supply the water returned to it by rivers. There followed studies of artesian water, relation of ground water to geology, and the hydraulics of open channel flow. Many detailed techniques and advanced concepts in current use were developed early in the nineteenth century. By the latter half of the century, detailed hydrologic studies of rivers and their basins were being made, and 1888 marked the beginning of the modern network of stream gaging stations. Recent advances in hydrology have been particularly stimulated by the rapid development of water resources of the United States. In the past twenty years, there has been an upsurgence of work on flood control, dam and reservoir construction, and soil conservations.

With the rapid developments in hydrology came a recognition of the need for modern treatment in the form of general textbooks, and it is fortunate that at present there are a number of up-to-date treatises. As a general summary, the text of Linsley, Kohler and Paulhus /13/ is outstanding.

Resource development has involved studies of storm rainfall /21/ and floods, their frequency, magnitude, and meteorlogic aspects /5, 10/; of infiltration, overland flow, and the effects of vegetation on those processes /7,9/; of hydrography analysis and flood routing /16, 8, 6, 14/.

Studies of floods brought hydrologists in close contact with meteorologists, and engineering agencies saw the need for applying techniques of meteorological analysis in estimating the maximum flood conditions for spillway design /2/.

Because the rate of infiltration of water into the soil is a major determinant of the amount of direct surface runoff from a given storm, the infiltration capacity of soils became a problem of major importance, studies of which involved not only engineers and soil scientists but plant ecologists as well.

Particular progress should be mentioned in physics of snow and snow melt /20/ and the subject of evaporation from lakes and reservoirs /17, 11/. In the field of glaciology, the Scandinavians have made far greater strides than have Americans /1/, but in the last few years there has been an increase of activity in this field in western United States and Alaska.

The problem of climatic change has received the attention of a large number of hydrologists as well as meteorologists and geologists /3/.

Relation to Physical Geography

In geographic studies the climatic factor has long been recognized as an important factor in delineating regional patterns. It goes without saying that climatology is a necessary tool for the geographer. Modern meteorology provides an increasing insight into the mechanism by which climatic patterns are maintained, and thus contributes to a better understanding of physical and biologic relationships inherent in geography. Modern training in geography

indicates a recognition that not only is climatology a tool necessary for the geographer, but some training in meteorology is essential to an understanding of how climatic patterns are fashioned from the statistical distribution of discrete weather events. In a similar manner hydrology provides an insight into those geographic phenomena influenced by water-land relationships.

Hydrology is analogous to both meteorology and climatology. Hydrology encompassing the study of discrete events, such as floods, is allied to meteorology. It is also the study of balances or average states, of which the occurrence and distribution of ground water is an example.

In the techniques employed, hydrology is again analogous to both meteorology and climatology. Modern meteorology is characterized by the application of advanced mathematics to the analysis of greatly over-simplified models. The simplification is necessary owing to the large number of variables and the comparatively meagre volume of observational data relative to the great spans of time and space. Hydrology utilizes such methodology, for example, in the studies of the movement of ground water. On the other hand, the application of statistics and the formulation of useful empiric relations as in the study of flood frequency is not unlike methods in climatology.

Hydrologic Factors and Geographic Patterns

In view of the direct influence on geographic patterns exercised by climatic factors, it may perhaps be less well appreciated that hydrologic factors also, at times, exercise considerable influence on the forming of geographic patterns. For example, consider a situation in which the availability of ground water has directly influenced the distribution of agricultural and municipal development. The example is also useful to demonstrate the fact that in certain areas in the United States, full utilization of available water has

already been accomplished and further expansion of population or industry will be seriously affected by the supply of water.

On the southern edge of the small island of Oahu, Hawaii, are concentrated three large users of water, the city of Honolulu (population 500,000), the Navy installations at Pearl Harbor, and two large sugar cane plantations. Except for one of the plantations which derives part of its water from a system of collection ditches in the nearby mountains, all of these activities depend on ground water pumping for their supply. The demands for water are high because this leeward section of the island has a high percentage of sunshine, and receives between 20 and 35 inches of rainfall annually. The two plantations alone pump from the ground 150 million gallons a day and have done so continuously for more than 40 years.

The sources of this ground water is the Ghyben-Herzberg lens, locally developed to unparalleled perfection. This lens can be thought of as a bubble of fresh water, which being lighter than sea water by the ratio 40:41, "floats" on the heavier saline water below. By inspection of Figure 1 it can be seen that the fresh water is entirely confined within the pores of the rock making up the island. Hydrostatic equilibriom dictates that at every point, each foot by which the free surface of fresh water lies above sea level, there must be below that point 40 feet of fresh on top of the salt water. The gradient of the ground water table, that is the slope of the surface of fresh water, is determined by the permeability of the rock or the resistance to lateral flow. The slope is maintained by the constant accretion of water resulting from seepage of infiltrated rainfall.

It is clear that pumping from the fresh water lens in excess of the accretion from infiltrated rain would gradually thin the lens and raise the

level of the fresh-salt boundary. A tremendous volume of fresh water accumulated during recent geologic time while the lens gradually enlarged until outflow equalled inflow. Drawing on this large supply, pumping might continue for a long period at a rate greater than the accretion before the reduced supply reached a critical point. It happens, moreover, because of the slow movement of water through the fine pores of the lavas making up the Oahu cone, that adjustments in the large fresh lens follow only slowly after pumping from the upper portion. So slow in fact are these responses that it is nearly impossible to compile accurately a water budget and so determine just what is the annual increment and thus the allowable pumping rate /19/.

The tremendous demands on the fresh water lens in the vicinity of Honolulu have locally raised the salt water boundary by important amounts, yet the adjustments are so gradual that it is impossible to define the allowable long-term-pumping rate from various areas. As a result, no one group has been willing to curtail pumping lest water which a person might have obtained be drawn from the common reservoir by his neighbor. Though the problem is not yet critical, there is every indication that for many years the waterusers have been drawing "capital" as well as "interest" from their bank. Wells formerly fresh have increased in salinity and Honolulu is now replacing deep pumps with shallow collection galleries to skim fresh water off the surface of the lens.

That these hydrologic principles are as important in geographic analysis as are climatic ones, can be seen by comparing land use maps with sources of water maps. The periphery of the island contains a band of sugar cane plantations located where cloudiness is low and sunshine high, but where shallow water is obtainable in wells. In a concentric band at higher elevations,

insofar as topography allows, unirrigated pineapple is grown where the rainfall is 35 to 100 inches.

The city of Honolulu is located on a harbor where whaling and the export of sandalwood once dominated the shipping. These products are now replaced by sugar, pineapple, and by the tourist industry. Honolulu is located on a narrow strip of shoreline and has perforce expanded into the precipitous mountains behind it. When Pearl Harbor became an important base, the city extended westward on to the hotter flats bordering the drowned valley which is the harbor.

The hydrologic circumstances surrounding the occurrence of groundwater in southern Oahu and the related inability to precisely assess the quantities of water allowable for indefinite use, are rapidly bringing that area to a critical point. Legal or administrative authority must allocate a limited water supply between a long established agricultural priority, an expanding municipal requirement, and a first order military establishment. That such decisions will provide an interesting new series of geographic developments seems clear.

The Oahu example is a particularly clear demonstration of how land use often changes radically at a topographic or other boundary line representing the economical limit of ground water pumping. The example also typifies the struggle between municipal and agricultural requirements for water. Similar conflicts can be cited in many areas in the United States.

There has been considerable discussion in the semi-technical press of the seriously depleted water supplies all over the United States. Though water shortages are serious in some localities, the problem is not as universal as some would have us believe. There is a definite need in the field of

hydrology for technically competent discussion in lay terms of problems and policies in the field of land - water relations. A distinguished example of much needed public education is a recent analysis of ground water supplies in the United States /18/.

Certain aspects of the interrelation of physiography, hydrology, and geography are well recognized. Particularly by the application of new hydrologic data, however, the area of overlap of the three sciences is a field of study of great potential interest to workers in each of the fields. By a brief discussion of an example, it may be possible to indicate first, how hydrology is related to geography through its bearing on physiography, and second, to suggest one of the many directions of study which appear mutually fruitful for the three fields.

Relation to Geomorphology

The example just discussed indicates that hydrology is a factor which must be included in study of geographic patterns. Further evidence is seen in the relation of hydrology to geomorphology. No explanation is needed in asserting that geomorphological concepts figure strongly in physical geography. A locality described as pediment surface immediately brings to mind a host of related facts regarding the climate, the nature of the soil, possible availability of water supplies, the ephemeral nature of stream flow and others. Landforms described in terms of a geomorphological region similarly provides an immediate picture in generalized terms of the character of the country. Geomorphologic terms to describe the type of river, drainage systems or patterns, and many other features of the landscape will convey to the reader correlative facts in proportion to his degree of acquaintance with the details of geomorphology.

The grading of rivers is a physiographic process of interest to geographers. In academic courses in geomorphology it is deemed sufficient to point out that most rivers rise in V - shaped youthful valleys where rushing water flowing on steep gradients is most effective as an eroding agent. Downstream is a zone of mature valleys where gradients are adjusted to the load. Emerging from the mountains, rivers meander lazily across a wide plan of low gradient.

We harbor a preconceived notion that because the slopes are steep in the headwaters of a river basin, the water velocity in the headwaters is greater than on the flood plain downstream. On the lower reaches of a river, we imagine water velocity to be relatively low and for this reason, the water transports only a fine grained sediment load which is deposited on the plain or carried out to a delta.

These ideas must be revised in the light of a hydrologic analysis of river grading. Inspection of actual measurements of water velocity shows that the velocity increases downstream in a river system. Imagine all points along a river and its tributaries to be flowing at an average discharge. Let each point on the river be discharging at a rate equal to its average annual flow. With increasing drainage area as one moves downstream, the average flow increases and therefore, the condition of average discharge at all points in the system implies an increase of flow toward the mouth in proportion to the drainage area above, Under such conditions, the velocity of water flow increases from headwaters to mouth.

For example, the Wind River at Dubois, Wyoming, a distant upstream tributary to the Missouri and thence to the Mississippi River, experiences a mean discharge of 30 cubic feet per second. The velocity corresponding to

this discharge at that point is 1.6 feet per second. The mean flow of the Mississippi River at Vicksburg, on the other hand is 550,000 cubic feet per second and the corresponding mean velocity is 5.3 feet per second.

Many examples might be cited, but it can be demonstrated that when the flow at various points along a river system is of a given frequency of recurrence interval, the velocity increases downstream. In simple terms, if a river is in flood and all tributaries are experiencing a flood of the same relative magnitude, the velocity increases downstream just as it does during periods of low flow /12/.

The explanation of the increase in velocity downstream lies in the fact that velocity is affected by depth and roughness as well as by slope. The increase in depth downstream over-compensates for the decrease in slope and a net increase of velocity results.

The fact that velocity increases downstream while, at the same time, size of the bed material decreases downstream, implies that velocity, through the medium of slope, is not the primary adjustment by which sediment transporting capacity is kept in equilibrium with the supplied load. Width of channel is just as important as slope in this adjustment process. At a given velocity and discharge, increase in channel width at the expense of depth decreases the capacity of the stream to carry suspended load.

It can be shown that adjustments to accommodate a changing supply of sediment take place primarily in channel shape and only to a minor degree in channel slope. These adjustments are surprisingly rapid and even during passage of a given flood wave, minor changes in channel shape occur through which an equilibrium of capacity and load is maintained. Contrary to our current conception, most river channels are in a state of quasi-equilibrium

at all discharges, both at low flows and in flood. The channel shape changes sufficiently fast to keep an equilibrium shape during all stages of physiographic development, youth and old age as well as maturity.

Some potential geographic implications of such a hydrologic analysis of a geomorphologic problem may be cited. River control through the construction of dams, levees, irrigation developments and power constitutes one of the most powerful forces affecting geographic patterns in western United States. Our ability to foresee how these patterns will develop as river control projects are constructed will depend to a large degree on our ability to foresee what changes in river regimen will occur. Sediment will be removed from the water by deposition in reservoirs behind the dams. The clarified water will tend to remould the channel with consequent adjustments in slope and channel shape. The control of a river during this adjustment will require further engineering work. Patterns of population, transportation, marketing and other phenomena of human occupance will necessarily be affected by the changes in river regimen.

Quantitative Hydrology in Problems of Physical Geography

An attempt has been made to indicate that the hydrologic factor is as important in geographic analysis as are the climate and meteorological factors. It has been asserted earlier that not only does it have direct influences, but it also has indirect effects on the hydrologic aspects of geomorphology.

There is a third way, in the writer's opinion, in which an understanding of hydrology is important in geographic study. The geographic effects of certain hydrologic factors will be highly sensitive to small differences in the quantitative values of these factors. In such a case, general principles are insufficient to evaluate the geographic effects of hydrologic changes.

The results may differ widely depending on the particular values of the variables involved. For example, the United States is progressing rapidly toward a more complete development of its water resources. It is recognized at the same time, that land resources must not only be developed in the direction of more intensive and economic use, but must be protected against deterioration of fertility and tilth and against undue soil losses by erosion.

The development of water resources by dams, reservoirs, river channel improvements and other engineering works has stimulated attempts to protect these works by improvement of general land-use practices. But it is difficult to evaluate the effects of land-use changes owing to the lack of proper hydrologic experimental data. The available data were derived from studies of small areas, and extrapolation to large areas involves two kinds of error, 1) small differences are magnified by the extrapolation and become significant, and 2) hydrologic functioning of large areas involves variables not present in the experimental data for small watersheds. Thus, geographic effects resulting from small changes of land use over large areas are difficult to forecast. The geographic effects of land use changes cannot be forecast on the basis of hydrologic principles because such forecasts require a level of quantitative knowledge not yet attained. Some details of this problem will now be discussed.

Though the amounts of sediment carried by different rivers is known in a general way, problems of reservoir design require much closer estimates of sediment loads than are now possible. Equipment for sampling suspended load of rivers has been radically improved in the past few years, but collection and analysis of these records are so expensive that expansion of the measuring network will proceed slowly. Moreover, it is clear that the unmeasured bedload

constitutes such an important percentage of the total load that expansion of the network and improvement of techniques in suspended load sampling will, in themselves, fall hopelessly short of the true target. Yet, the bedload problem is so complicated that serious attempts at field measurement are still small indeed compared with the suspended load sampling effort. To bring these programs of investigation into proper balance is an administrative problem of high priority in the hydrologic field.

In the construction of large reservoirs the effects of lack of data on rates of sedimentation can, in effect, be eliminated by providing sufficient dead storage that reservoir sedimentation will be rendered unimportant during the period of repayment of construction costs. By this means, river control by reservoir construction can, under current economic reasoning, be made independent of problems of land use and condition on the contributory drainage area. From the standpoint of long-term resource development and conservation, such independence is unfortunate.

Land use practices can affect water supply, sediment contribution, and the magnitude and frequency of floods, but the direction and magnitude of these effects are dependent on a host of local and regional factors. Were significant net gains of a beneficial character demonstrable as a result of land treatment measures and conservative land use practices over large watersheds, then the public desire for power irrigation, and flood control could be effective levers in implementing programs of conservation on the ground.

At the present time programs for erosion control and watershed retardation are found justified in many areas only by inclusion of benefits accruing from subsidiary effects of the program. The often specious reasoning necessary to show a favorable cost-benefit ratio for land conservation work reflects

not only a curiously monetary economic philosophy but a serious lack of basic hydrologic knowledge. The discouraging aspect of the problem is that the collection of adequate hydrologic knowledge for full evaluation of the effects of land use programs is neither vigorously prosecuted during the planning of a proposed program nor included in the plan as an integral part of the field installation. At this rate we will continue to decry our inability to justify land treatment measures on their own merit. At the same time we tolerate wholly inadequate programs for the collection of the basic data necessary to provide sound quantitative evaluation of the conservation measures which we wish to justify.

Field experiments to examine the effects of various land use practices on water and sediment contribution have generally been restricted to watersheds smaller than a few square miles. Quantitative data on infiltration capacities of soils are available for only an insignificant percentage of the total number of soil-vegetation complexes on which land use treatment will be applied if federal programs now contemplated become realities.

Experiments on small watersheds have demonstrated conclusively that restoration of deteriorated vegetative cover reduces erosion and reduces the sediment outflow. That the same principles apply to large watersheds seems clear. However, in many western rivers flowing in unconsolidated alluvium, large volumes of material are available for transportation by the river. If the sediment concentration of the water contributed by small tributaries into the channel of the master stream has been reduced, it is possible that the clarified water may pick up sufficient material out of the stream bed to deliver in downstream reaches nearly as much sediment as was delivered before the watershed vegetation was restored.

As an example, in planning a program of land treatment, it is often asserted on the basis of meagre data, that the proposed measures such as terracing, reseeding, erosion control structures and water spreading, will lower the rate of sediment production but will have insignificant effects on water yield. Such a conclusion may be based on values of infiltration and transpiration derived from experimental plots or small watersheds. Slight errors in extrapolating these values to apply to large watersheds could make a great difference in the final results.

To recapitulate, general knowledge of hydrologic processes provides a perfectly sound basis for anticipating the types of effects and interactions which might be expected as a result of a large scale and intensive modification of present land use practices. These effects, known in principle, are so dependent, however, on the quantitative values of the many variables involved, that even the direction of change of factors such as total water yield as a result of a conservation program, may not be possible to determine. Changes in land use, even though small, when applied to large areas of land, set in action a host of interdependent reactions. So complicated are these variables that detailed quantitative data of hydrologic character are necessary for determining the results.

It was stated that such changes in land use patterns had geographic implication of great potential importance. To foresee the effects of changes in land use on geographic patterns, must in effect, depend to a large degree on quantitative knowledge of hydrologic factors. Problems of land use and changes in use impinge on occupance and other aspects of geographic patterns. It will be realized, on reflection, that the American view of land stands in contrast to views of many other societies. Owing to relative land and scarcity

in Europe emanating particularly from Feudal times, the necessity for intensive use of land helped cultivate a philosophy of responsibility and husbandry as yet lacking in America. The typical American farmer feels no ethical compunction if his land is cut with gullies - only an economic regret or and ache in his back after plowing. Two forces will gradually press toward the assumption of an ethical responsibility; economic, as land scarcity forces more intensive use and preservation of land; and scientific, as the facts accumulated by research more clearly delineate the interrelations of land practices and the disposal of water and erosion products. In the latter respect, hydrology holds the reins.

Status and Trends

It has been asserted that hydrology is related to the general field of geography in three primary ways. First, hydrologic factors may affect geographic patterns directly. Second, hydrology acts through geomorphology. Many problems of current interest to hydrologists are fundamental to an understanding of geomorphology. Third, quantitative values of hydrologic variables are often the key to prognosticating the effect of hydrologic changes on social and agricultural patterns. A general knowledge of principles is not necessarily sufficient to evaluate the effects of even small changes in land-water relations, when these changes affect geographic regions.

Perhaps the most important effect of present trends in hydrology concern the quantitative evaluation of geographic effects of small variations in hydrologic variables, particularly those related to land use. Such quantitative data will provide the basis for evaluating many different kinds of changes which occur in water-land relations. Climatic change and its affect on land use patterns is one example. The effect of large scale river

development is another. These are effects of such application that the importance of the hydrologic factor in geographic study will certainly become increasingly clear.

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PHYSICAL OCEANOGRAPHY

Introduction and Background

There are problems in attempting to speak for the oceanographer to the geographer, or fully to assess the place of oceanography in a survey of physical geography. Modern oceanography is an extensive and rapidly expanding field. Workers in oceanography include physicists, meteorologists, chemists, biologists, and geologists. There is a wealth of diverse information already available and intensive current research on many unsolved problems is underway. Actually, there is a geography of the oceans almost as broad in it biological and physical ramifications as the geography of the land portions of the earth.

Ocean areas constitute almost three-fourths of the earth's surface. The oceans have important influences on weather and climate, on landforms, and on transportation and other vital economic pursuits. A detailed treatment of the different aspects of the oceans may be gained from the treatise by Sverdrup, Johnson, and Fleming /1/. The present discussion is concerned with the physical basis of oceanography and with certain implications resulting from it.

It is instructive to compare this work /1/ with such earlier treatises of comparable scope and intent as Reclus' The Ocean /2/. One finds a decided change in the nature of the presentations over the last century or so, the later works being much more technical and quantitative than the earlier. This trend is not peculiar to oceanography, but is characteristic of all modern scientific disciplines underlain by physics, chemistry, or mathematics.

Several developments have favored this change. The growth of instrumentation, made possible by advances in applied physics, has led to an increased precision of measurement. More widespread interest in oceanographic problems, often motivated by practical considerations, has brought about surveys,

expeditions, and programs of systematic measurement which are relatively extensive when compared with similar projects in the past. But profounder than these, so far as physical oceanography is concerned, has been the gradual development of a fairly secure mathematical basis for theoretical researches. Much of this review will be devoted to an elementary exposition of this mathematical basis and a survey of some recent results that have been obtained with it.

Further, in physical oceanography, the motion of the water is of primary importance and must be understood before other problems can be attacked. Hence, attention is given to waves and currents and to the effects they produce.

Studies of ocean currents are based on the classical equations of motion in the Newtonian physics. The first adequate theoretical accounts were given in the present century. Among them is Ekman's theory of wind-driven currents, which lead directly to the description of the upwelling phenomenon which so delights the student of physical oceanography when he first encounters it. The account of ocean currents given below rests directly on Ekman's theory.

The classical solutions for both waves and currents neglect the effects of turbulent friction and these effects are among the most important contemporary problems in oceanography. Rossby and his collaborators have attempted solutions which take them into account and have shown that the classical formulations represent only first approximations which may, in some instances, be quite wide of the mark.

Scientific Method in Oceanography

The scientist from another field who examines work in oceanography is often disturbed (unless he is a meteorologist) by the marked contrast between the level of theoretical sophistication at which the physical oceanographer operates and the crudity of the data that can be obtained. The influence of

many uncontrolled sources of variation usually makes physical measurement in oceanography highly unrealiable, yet the physical oceanographer does extensive theoretical work in connection with his observations, partly because the observational data are so crude and partly because of the close ties between oceanographic phenomena and portions of experimental and theoretical physics.

In laboratory sciences, the classical scientific method is to remove scources of variability by rigid experimental controls and to theorize only after the basic processes are reliably established. Most of the material dealt with in oceanography must be taken in its natural context, a context involving complex interactions among various processes which proceed simultaneously and whose effects must be dealt with as they occur. Furthermore, the data which the oceanographer obtains are often essentially incomplete. Gathering data at sea is an expensive operation so that, in normal circumstances, an adequate coverage of even a relatively small region for a short period of time does not frequently occur. Most sets of oceanographic measurements are fragmentary with respect to the factors affecting the phenomena under scrutiny and are widely scattered in space and time. In view of these fundamental limitations, the oceanographer is occasionally asked by sophisticated scientists, from disciplines in which the measurement problems are not so acute, why he does not confine himself to simple correlational studies among various aspects of his crude data. He must defend his extensive theorizing about phenomena so incompletely understood.

The first point in his defense is that the theories he uses are not based on oceanographic data, but are largely taken over from experimental and theoretical physics. Whether he deals with ocean currents, radiation, water waves, or processes of diffusion the basic theory employed is of unquestioned

validity in other contexts. These fundamental physical processes have been thoroughly studied. The oceanographer assumes that their operation in the phenomena he studies is essentially the same as their operation elsewhere provided that, in applying the principles describing them, he makes due allowance for such special conditions as may occur in his problem.

The second point is that the use of theory is necessary precisely because the data are fragmentary and unreliable. His only hope of making more than a series of isolated observations out of data obtained at different times in different regions of the oceans is to build a theoretical framework encompassing all the observations. To this, each observation contributes and his success in fitting a theory to the scattered observations adds to our understanding of the phenomena and usually provides sufficient justification for his theorizing. If his measurements are highly unreliable, very large collections of data would be necessary to establish significant covariations between two or three aspects. Demonstrated physical processes are presumably among the major sources of variation. The oceanographer attempts to remove the effects of these processes by means of his theory. Occasionally, he finds that, when the obscuring effect of variability attributable to some large-scale physical process has been removed from his data by theoretical manipulation, relationships between other aspects become fairly obvious.

The third point is that he does not pretend to make highly accurate predictions. A glance at the graphs in The Oceans, for example, will show that the physical oceanographer is content at present to obtain a rough correspondence between his theoretical analyses and the data available.

Physical Oceanography

1. The theoretical picture.

Ocean water can be characterized by such physical and chemical properties as temperature, pressure, density, conductivity, salinity, and chlorinity. At any given time the water in a given place has unique values for these physical and chemical variables. The physical oceanographer works toward a complete description of the distributions of the physical and chemical properties of sea water and the temporal changes in the distributions. He considers the ocean as a bounded system in which changes are affected by external processes at the boundaries of the system and by internal processes which depend only on the properties of the system.

The nature of the problem and the kinds of processes which must be considered might be clarified by the examination of a specific example. Suppose that the distribution of temperature throughout the ocean was known exactly at a certain time in the past and it was desired to calculate the distribution after a given time interval. Knowledge of the following factors would be required. (For an exact solution, the spatial and temporal distribution of each source of energy must be known.)

a. The radiation absorbed and emitted at the sea surface.

b. The heat interchange with the atmosphere due to convection of sensible heat.

c. The interchange of mechanical energy with the atmosphere.

d. The evaporation and condensation of water vapor at the sea surface.

e. The convection of heat at the ocean bottom.

f. The gain or loss of heat at the mouths of rivers due to the influx of water with its own characteristic temperature.

g. The transformation of mechanical energy into heat due to internal friction in the ocean water.

h. The transformation of mechanical energy into heat due to bottom friction.

i. Heating due to chemical or biological processes within the ocean.

j. The extent of turbulent mixing within the ocean and its effect on the distribution of temperature.

k. The extent of transformation of heat into the mechanical energy of thermal currents.

No oceanographer has, of course, attempted a complete solution of this kind, but these are the processes he would consider if he did. In the analyses of certain gross features of temperature distributions which have been made /1/, some of them have been considered. Others have been shown to have negligible large-scale effects.

It is of interest to note that the theoretical framework built by the oceanographer is nearly adequate, in a formal sense, for the solution of his problem. In order to see this, we shall re-state the problem somewhat more precisely than above. Neglecting biological phenomena, the independant variables are pressure (p), temperature (T), density (ρ), the concentrations of m chemical compounds (C_1, C_2, ..., C_m) and three velocity components (v_x, v_y, v_z). There are other physical variables such as electrical conductivity, but these variables are known in terms of the variables given above. The basic problem, therefore, is to express these m + 6 variables as functions of the three space coordinates (x, y, z) and time (t). For this purpose, the following knowledge is available.

a. Density is determined by pressure, temperature, and chemical

constitution.

$$\rho = f\,(p,\ T,\ C_1,\ C_2,\ \ldots,\ C_m) \qquad (1)$$

b. The hydrostatic relation holds between pressure, density, and depth. In differential form,

$$dp = -g\,dz, \qquad (2)$$

where g is the acceleration of gravity and the z-axis is taken positive upwards.

c. The equations of motion on a rotating globe must be satisfied. If friction is neglected, these three equations may be written in a single vector equation

$$\dot{V} = g + C - \frac{1}{\rho}\nabla p \qquad (3)$$

where $\dot{V}$ is the acceleration of a material practically of unit mass, g is the acceleration of gravity, C is the force due to the earth's rotation, and ∇p is the pressure gradient. For many investigations, friction cannot be neglected. The inclusion of its effects in the theory results in the addition of another acceleration on the right of /3/ and in the introduction of a coefficient of viscosity. Thus far, attempts to find a general expression for the coefficient of viscosity in terms of the other variables have been only moderately successful /3, 4, 5, 6/.

d. The classifical notion of the conservation of mass finds expression in the equation of continuity of mass.

$$-\frac{\partial\rho}{\partial t} = \nabla\cdot\rho V \qquad (4)$$

where standard vector notation has been used. A verbal statement of the content of equation /4/ would be: <u>The rate of increase of density in the vicinity of a given fixed point is equal to</u>

the rate at which mass converges on the point from elsewhere in the fluid.

e. For each chemical substance, an equation of continuity must be satisfied. These equations have the form:

$$\frac{\partial C_j}{\partial t} = -V \cdot \nabla C_j + D + R \qquad (5)$$

In equation (5), $\frac{\partial C_j}{\partial t}$ is the change in concentration at a fixed point, $V \cdot \nabla C_j$ is the decrease in C_j at that point due to advection, D is the change due to diffusion, and R is the rate at which the given chemical compound is added to the fluid at the point in question. The evaluation of D is closely related to the problem of evaluating friction and has approximately the same status at the present time. Both depend upon the extent of mixing which, in turn, depends upon the basic physical variables and the state of motion of the fluid. For certain substances, such as salt, the assumption that R = 0 can be made. Since the overall amount of such substances present in the ocean is affected only by processes at the boundaries, they are called conservative. The concentrations of certain other substances, of which oxygen is an example, are subject to relatively important effects of processes occurring within the ocean. These are called non-conservative.

Equations (1) to (5) are seen to be m + 6 in number when it is remembered that (3) and (5) entail three separate and m separate equations respectively. Thus, we may state that any problem in physical oceanography can be solved provided that:

a. Processes at the boundaries can be adequately evaluated.

b. The regions in which given substances of interest for the problem

are emitted into or removed from the fluid can be delimited and their rates of emission or removal computed.

c. The effects of mixing can be neglected or calculated.

d. The technical mathematical problem of solving the differential equations can be achieved.

In actual research, the oceanographer always simplifies the equations as drastically as he can. Unless, for example, he is investigating oxygen content for its own sake he would not attempt to take this variable into account in his computations of density. The major variables affecting density are salinity and salinity and temperature and these are all he ever uses when he is interested in density. Considerable success has been achieved in describing oceanographic processes in terms of the theory outlined above.

A moment's reflection on the problem as it has been stated and the general outline of the theory for dealing with it will reveal that knowledge of the state of motion is of fundamental importance for understanding oceanographic events. Since much theoretical and observational effort has gone into investigating various limited aspects of the motion and some of the most interesting recent research centers on them, we shall proceed next to a brief consideration of several selected aspect.

2. Currents in the surface layer.

A tremendous amount of observational material on surface currents has been accumulated and charts showing the general pattern of the surface motion are widely available /1/. Comparison of such a chart with a chart of average wind patterns in the atmosphere reveals considerable correspondence in the major features of the distributions. The close similarity between these two patterns is interesting in itself, but achieves an added increment of interest

from certain theoretical issues which have arisen in connection with the surface currents.

A steady current cannot exist at any depth unless the isobaric surface at that depth slopes relative to the level surface. This means that the existence of a steady current at the ocean surface implies a slope of the free surface. Because of the influence of the earth's rotation the current runs at right angles to the direction of slope of the surface with the surface high to the right of the current and low to the left in the Northern Hemisphere.

It follows that there must be a permanent non-homogeneous distribution of mass accompanying the ocean currents. It is possible that this non-homogeneous mass was brought about and is maintained by thermal (more properly thermo-haline) effects in a manner similar to that outlined by Bjerknes and his collaborators /7/ for the atmosphere. It is also possible that the mass distribution was brought about and is maintained by the stress of the winds, or, of course, by some combination of the two factors. Recent investigations /8, 9, 10, 11/ indicate that perhaps the wind stress alone may be sufficient to account for the observed mass distributions and currents.

The wind stress causes currents in the water. These currents are of such a nature that there is a general transport of water in a direction to the right of the wind direction in the Northern Hemisphere and to the left in the Southern Hemisphere. Thus, under certain conditions water would tend to pile up to the right of the wind in the Northern Hemisphere. This piling up results in a mass distribution which in turn results in a current. The current is not, as was naively thought at an earlier date, a simple direct effect of the wind stress but a secondary effect from the accumulation of water that results from the stress-induced mass transport. In these terms, it follows that it is the

vorticity of the stress field, rather than the simple stress, which is important /11/. This point can be clarified by a simple example.

Suppose that the atmosphere was in motion only over a limited portion of the ocean and that in this region the winds were westerly, strong to the north and progressively weaker toward the north. The strong winds in the north would cause a large transport of water into the region; the weaker winds to the south would cause a smaller transport of water out of the region. Under these conditions, mass must accumulate inside the region and a current would flow with the high surface due to the accumulated water on its right. This current would then be westerly in the North and easterly in the South, although it is brought about entirely by a west wind. Computations of the major features of currents and mass distribution based on the vorticity of the wind stress give the observed order of magnitude. The deviations seem small enough to result from inaccuracies in the observations, so that the possibility of an almost complete dependence of ocean currents on the wind field is indicated. It is possible that this knowledge may lead to fair predictions of deviations in the ocean currents from their average position.

Other current research of importance and interest is the investigation of transient eddies in the Gulf Stream /12, 13/. Of particular interest is the development of large-scale eddies which separate from the main stream and meander.

3. Wind, Sea, Swell, and Surf.

The importance of surf conditions for landing operations in World War II gave impetus to extensive research on short period surface waves. Results of this research are summarized by Sverdrup and Munk./14, 15/. Qualitative observations indicate that these waves are formed by wind stress; hence, in principle, it should be possible to predict the wave characteristics whenever the wind

field is known.

In the theoretical approach the energy imparted to the water by the wind is computed. This energy gives a motion to the water particles which is described by the wave equation. The energy received is broken up into two parts, associated respectively with the height and period of the waves, by a somewhat artificial partition whose physical significance is not clear. Following this partition, it is possible to compute the height and period of the waves in the generating area in terms of the integrated effect of the wind for its fetch and duration. The results are in good agreement with available observations of waves and wind in the generating area, an agreement brought about, in part, by the selected partition of the energy. The wave height which is calculated is approximately the average height of the highest third of the waves present and the period is that associated with these significant waves.

After the waves have been generated they leave the generating area and move as a train. The wave front (a region of sharp transition from low to high waves) moves with a characteristic group velocity. During this movement the height of the significant waves decreases and the period associated with them increases. This phenomenon is handled by means of an interchange of the energies associated with height and period. From a knowledge of the wave characteristics in the generating area and the distance over which they must travel, it is possible to compute the height, period, and arrival time of the resulting swell at a distant point.

Sverdrup /16/ has re-examined the increase in period and decrease in height of the significant waves during the travel from the generating area. He assumes a spectrum of impulsively generated waves in the generating area and shows that, on the basis of conservation of energy, one would expect the

height of the waves at the wave front to decrease, but not so rapidly as in the earlier theory. He then introduces air resistance as an additional factor and obtains results in general agreement with the earlier theory but which show that the previous theory was an oversimplification, since in the new theory the characteristics of the decay process and movement are not completely determined by the height and period of the waves as they leave the fetch. When the effect of air resistance is considered the theory predicts that short period waves will die out first, in agreement with observations that swell is longer and smoother than waves in the generating area.

Interest in surf conditions has stimulated research on the transformations of waves as they near the shore. The refraction effects of the bottom /17, 18/, longshore currents due to water transported by the waves, and the movement of sand on both shore and bottom due to wave action and longshore currents have received attention.

Many interesting and important theoretical problems remain in the study of wave generation, modification, and decay since the theory remains quite tenuous at several points. Yet the general system has enjoyed considerable success in the prediction of wave phenomena from weather data.

There are many other wave phenomena in the ocean such as tides, tsunamis, internal waves, and surf-beats. In view of space limitations these will not be discussed.

4. Water masses and underwater currents.

A mass of water can be identified by its physical properties and chemical content. The most important variables used in this identification are temperature and salinity. Rather uniform geophysical processes tend to produce systematic differences in the water characteristic of various oceanic

regions. In regions of high evaporation, the water tends to have a high salinity. In warm regions, water temperature is characteristically high. In cold regions where there is a large influx of fresh water from the mouths of rivers, water of low temperatures and low salinity is formed. In the Gulf Stream system, water of high salinity is cooled as it moves northward, forming a water mass characterized by high salinity and fairly low temperature.

As a water mass moves from its place of origin its temperature and salinity are gradually modified, yet the water mass can be traced as it moves from its source. In general, a water mass cannot be identified by a single value of temperature and salinity since these quantities are subject to variation in space and time. Rather, the identification is by means of a characteristic temperature-salinity curve. The possibility of tracing the movement of water masses through measurements of temperature and salinity enables the oceanographer to construct the patterns of deep water flow. Currents in the ocean depths have not been accessible to direct observation, but measurements of temperature and salinity can be made at any depth. The detailed results of such analyses are presented by Sverdrup, Johnson, and Fleming /1/.

Some Climatological and Ecological Aspects of the Oceans

As water masses move their properties are modified very slowly. The conditions which give rise to the formation of characteristic masses are relatively uniform from year to year. Over large regions in the ocean, the only changes in climatological conditions which can occur, aside from the surface layers, are due to the influx of water masses formed elsewhere in the ocean. The deep water in these regions remains remarkably uniform over long periods of time. Even in the surface layers, accessible to the effects of solar radiation, evaporation, and interchange of energy with the atmosphere, changes tend to be rather slow

because of the physical properties of sea water. Its high heat capacity and a high latent heat of evaporation tend to keep changes in temperature small and gradual. In this connection, it should be noted that ocean-living animals have not developed the complex temperature regulating mechanisms necessary to land animals.

In the highly stable deep-water environments, marine organism become closely attuned to the prevailing mean conditions so that slight environmental changes from place to place produce recognizably different organisms. An interesting phenomenon resulting from slow diurnal changes in the amount of light at intermediate depths is a diurnal vertical movement of organisms to preserve optimal conditions. The upper layers and regions near shore where conditions are less uniform are inhabited by more mobile and adaptive organisms. It is possible to divide the oceans into more or less clearly defined climatological regions, each occupied by organisms of specific types with little overlap in the forms of life.

Interrelations of Oceanography and Other Earth Sciences

1. Oceanography and climatology.

The influence of the oceans on average weather conditions has long been known. There is a vast difference in annual and diurnal air temperature changes over land and over the water. Over land, the radiation from the sun does not penetrate deeply. The major effect of the radiant energy is confined to the very crust of the earth. As the temperature of the earth's crust is raised, the air immediately above the earth is warmed to a considerable extent. In the ocean, an entirely different situation obtains. Because of the transparancy of the water, radiant energy penetrates to considerable depths. In addition, the ever-present motion of the water gives rise to turbulent mixing by

which the heat energy is carried downward from the surface. Hence, temporal differences in radiation cause much larger temperature changes in the lower layers of the atmosphere over land than over water.

It follows that a region in which ocean winds prevail will have a mild climate with only moderate swings of temperature as compared with a region not under the influence of ocean winds. Through the belt of the westerlies in mid-latitudes the west coasts of continents enjoy these mild maritime climates in contrast to the east coasts which are marked by the large diurnal and annual temperature changes characteristic of the middle sections of the continents.

The influence of the ocean described above is present independently of the effects of any particular current systems that may exist. Cold or warm currents carrying abnormally cold or warm water to given points on the coast may, it is true, cause a temperature anomaly at those points over and above the general influence of the oceans on the climate; but the maritime climate of the west coast of Europe and Africa would continue even if the Gulf Stream were diverted.

2. Oceanography and meteorology.

The close relationship of these two fields is apparent in much of the previous discussion where important influences of the atmosphere on the ocean have been indicated. If the oceanographer is to use his present theories of ocean currents and of wind waves and swell for forecasting purposes, he needs accurate meteorological information. Typically, the oceanographer is concerned with weather patterns over the ocean, where meteorological stations are widely scattered and considerable extrapolation is necessary to form a picture of the weather over a large area. Hence the oceanographer welcomes advances in meteorology which indicate new measurements that can be made at each station

so that extrapolations are based on more extensive data.

The meteorologist has always been interested in the modification of air masses over the ocean and in these days of transoceanic flying his interest has been increased. Some direct work on this problem has been performed. During the winter months there are frequent outbreaks of cold, relatively dry air moving from the east coasts of continents out over the water. Under these conditions, instability exists in both air and water and a violent flux of sensible heat and water vapor into the atmosphere occurs. The problem of handling friction theoretically is relatively simple in the presence of such intense turbulence and it is possible to compute the modification of temperature in the atmosphere quite successfully /19/. The increase in the water vapor content is not so easy to compute and this aspect of the problem remains unsolved.

An extensive amount of theoretical and observational labor has been expended in the investigation of air mass modification over the water when the air is warmer than the water and conditions of stability are present /20, 21/. This problem is exceedingly difficult and has not, to the author's knowledge, been adequately solved.

The location of storms at sea can seldom be very definitely established. Off the major shipping routes, weather reports are widely scattered so that the meteorologist must often map the entire ocean from as few as eight or ten reliable reports. With the development of wave recording instruments long, low waves arriving well in advance of the visible swell from a storm have been discovered. A technique has been suggested for using such waves to track the movement of the storm in which they were generated /22, 23/. There are indications that, with adequate wave recording facilities, a complete analysis of the records of these waves would make possible computation of the size and

intensity of the storm as well as its location. The information added by this tool, if it proves usable, will be invaluable to the maritime meteorologist.

Applied Physical Oceanography

There are a variety of practical problems of importance to industries, shore communities, the military establishment, and others which require the technical advice of someone well acquainted with the principles of physical oceanography for their adequate solution. In this section, a small sample of such problems will be presented, with a few comments relative to each.

1. Many seaside communities have set up sewage disposal plants which utilize the ocean as a dumping ground. These communities frequently discover that the sewage is returning to pollute their beaches. In some cases, an oceanographer could have predicted this and could also, at a small added cost to the community, have arranged the sewage disposal so as to avoid the resultant beach pollution.

2. At many points along our coasts, breakwaters have been erected for various purposes. The breakwaters disturb the pattern of currents along the shore, and over a period of years, there is a filling of sand on one side of the breakwater and a cutting away of the beach accompanied by considerable damage to valuable property on the other. This result could invariably be predicted by a physical oceanographer. If such a person were consulted during the planning of a project of this kind, he could usually place the breakwater in a position where property damage could be minimized.

3. Various industries build structures offshore, sometimes in water of considerable depth. Here, an oceanographer can estimate the maximum stresses to which the structure will be exposed, providing information of value to the engineer.

4. The fishing industries notice seasonal migrations of various fish. Occasionally the fish migrate out of season and some time elapses before they are again found. On the hypothesis that these migrations are determined by anomalies in the physical properties of the water, oceanographic study of the problem might well be worthwhile. One applied research project of this kind is already in existence.

There are a large variety of projects in which oceanographic (geological, biological, chemical, and physical) knowledge is nearly indispensable. Certain industries have long recognized this and have utilized oceanographers as consultants or secured trained people to work directly for them. There is, however, a dearth of what might be called "oceanographic engineers" and an unfortunate general ignorance of the amount of oceanographic information available and the uses to which it can be put.

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